Development of the *Topmetal* CMOS Pixel Direct Charge Sensor

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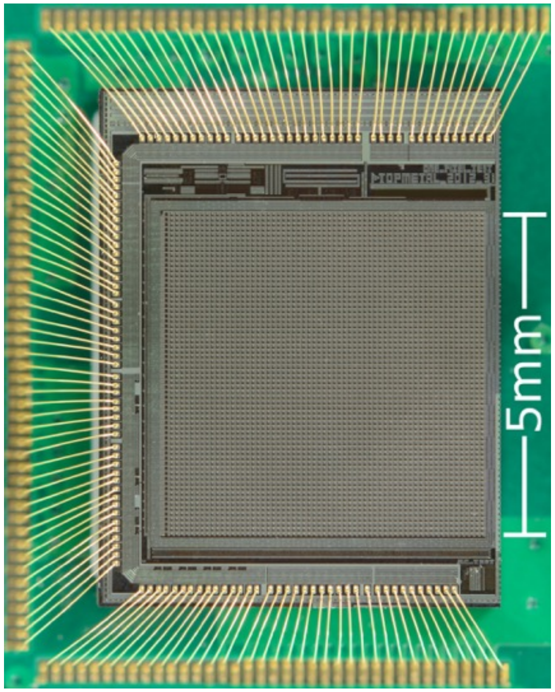
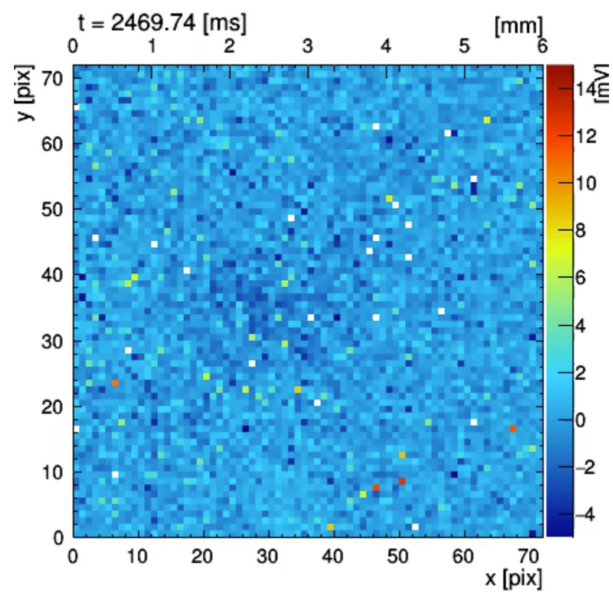
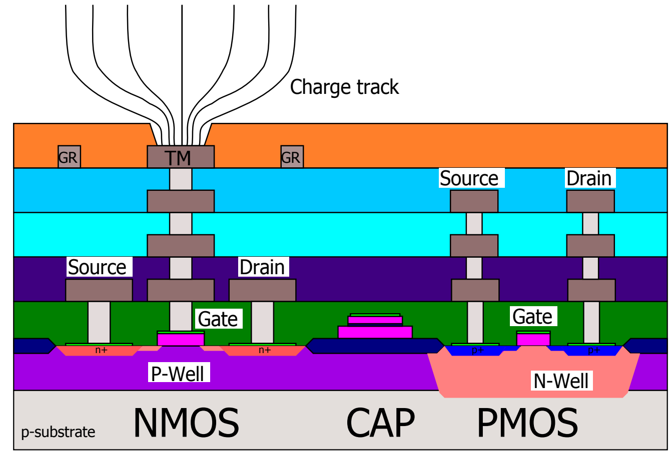
Lawrence Berkeley National Laboratory

Topmetal: started since 2012



Alpha ionization tracks



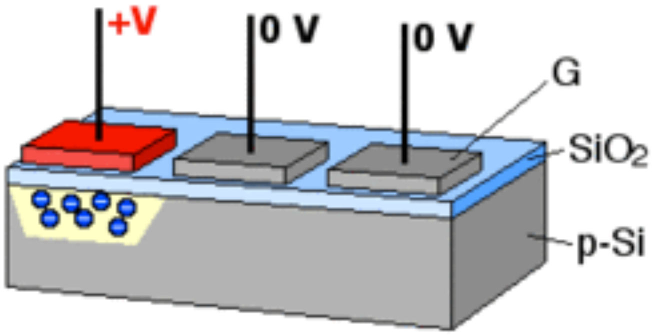


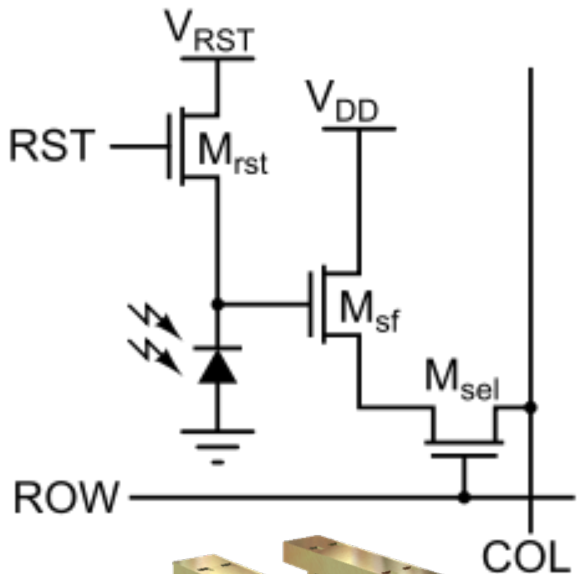
Personnel:
Yuan Mei
NSD weak interactions
Postdoc (2011-2015) Staff (2016-)
+ UCB undergrad students
+ Visiting students/faculties

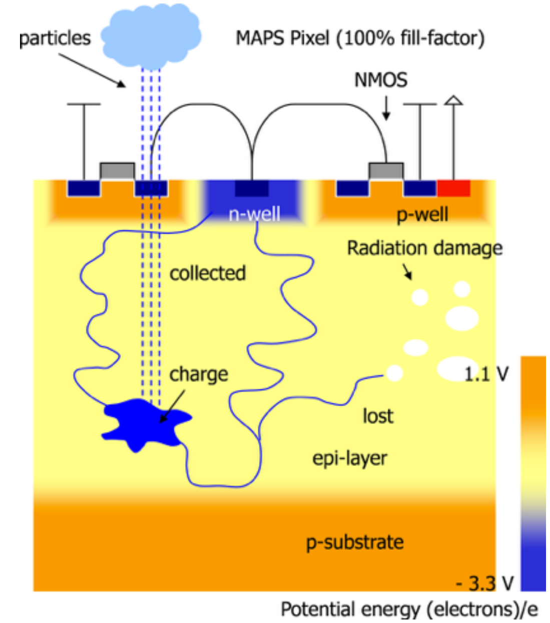
Collaborator:
Xiangming Sun
Formal RNC postdoc,
HFT development until 2013
Now Professor, Central China Normal University (CCNU)

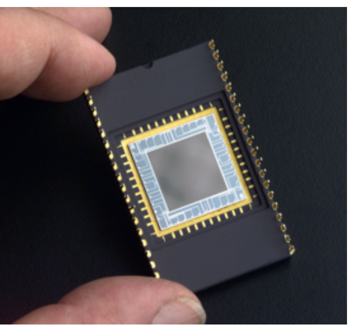
- 80X80μm pixel size
- Direct charge collection
- Standard 0.35μm CMOS process, no post-processing
- First version (2012), high noise & high bandwidth
- Second version (2014), <15e- noise on each pixel. In-chip signal processing, good for large scale array
- Third version (2016), specialized design for 0νββ LDRD support since 2015

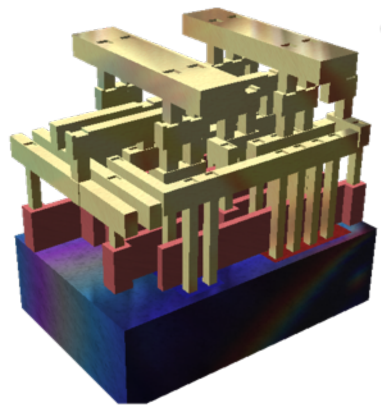
Motivation: (1) silicon pixel devices



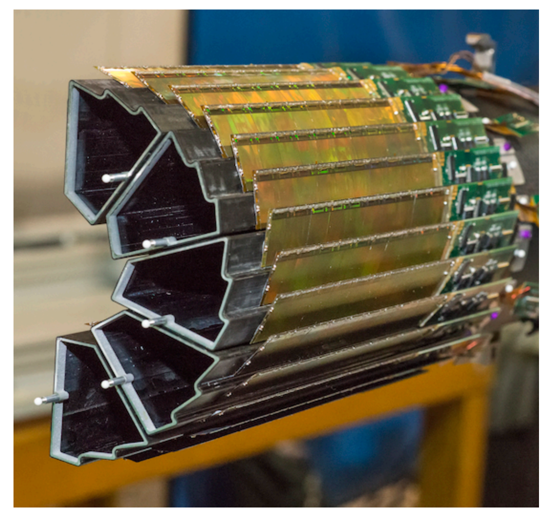








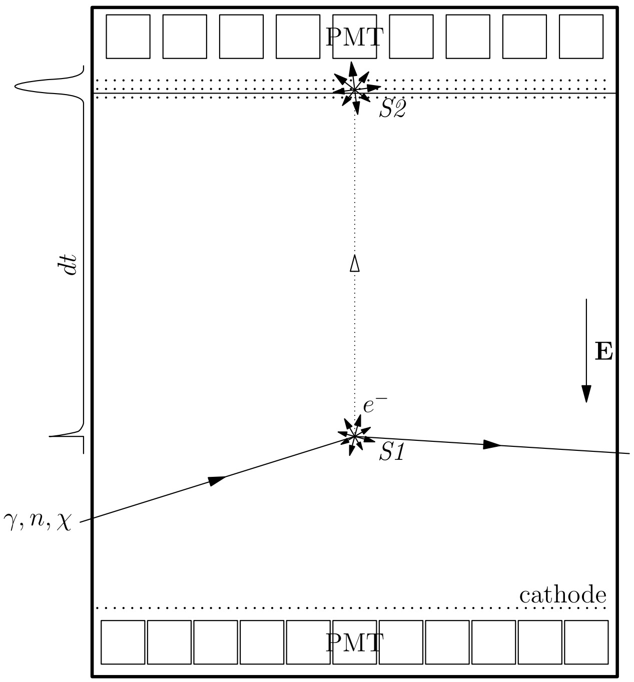
- CCD → Active pixel
  → Monolithic Active Pixel Sensor (MAPS)
- Charge generated in silicon
- Mature CMOS processes are becoming affordable
- Designing Integrated Circuit (IC) is becoming similar to designing Printed Circuit Board (PCB)



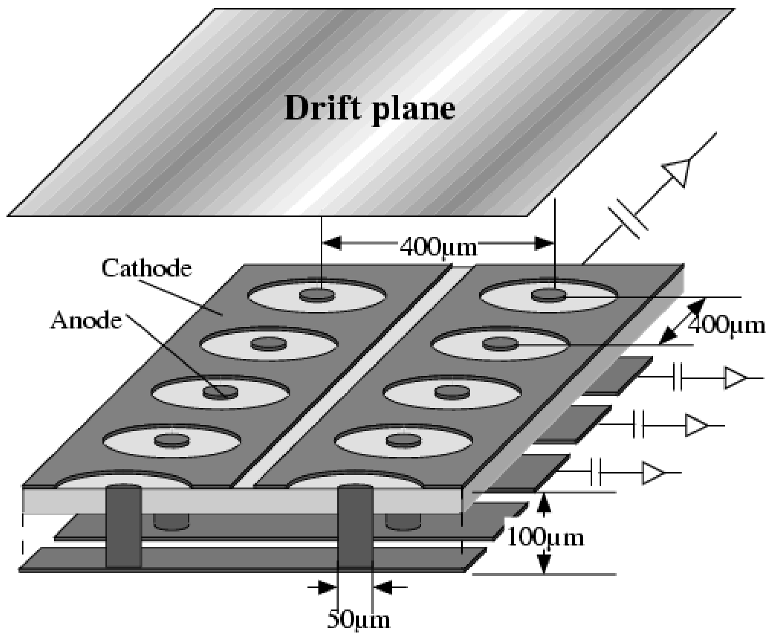
STAR Heavy Flavor Tracker

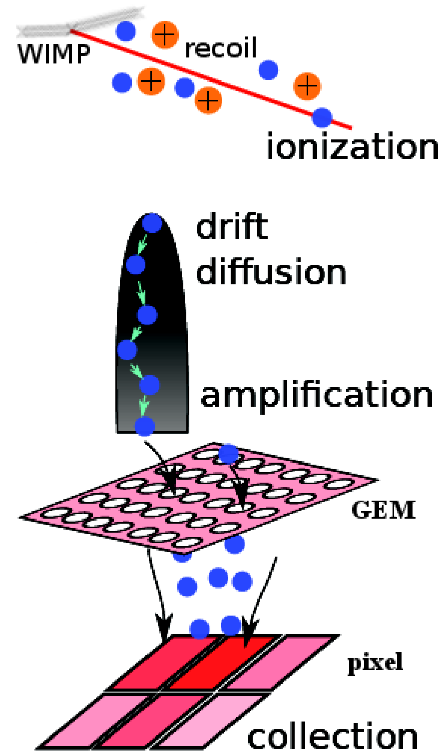
Motivation: (2) charge readout in TPC

Goal: detect small charge tracks



XENON100, LUX, LZ, etc.





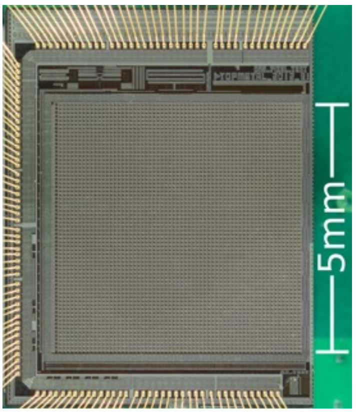
S.E. Vahsen et al.
http://arxiv.org/abs/1110.3401

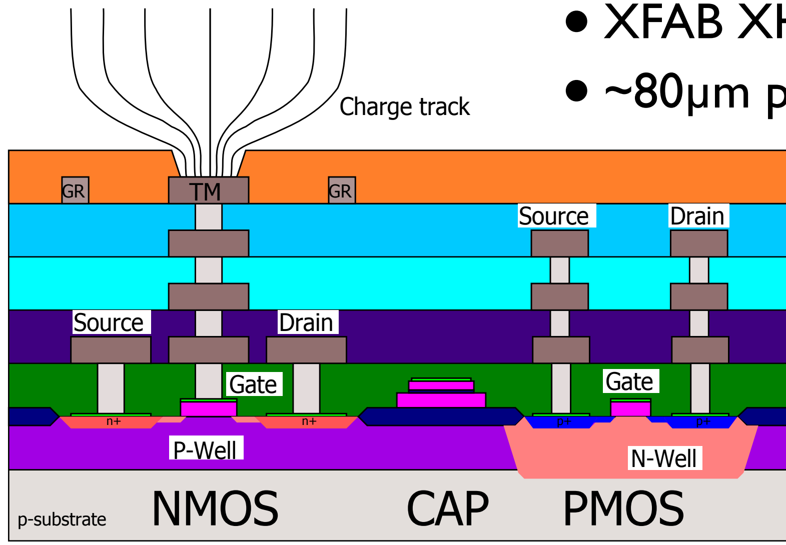
- Liquid Xenon TPC
- Time Projection Chamber
- Wire and/or light readout
- mm~cm spatial resolution

- μ-PIC (Micro Pixel Chamber)
- Printed Circuit Board technology
- 400μm pitch
- Some electron gain in gas
- Difficult for readout and scale-up

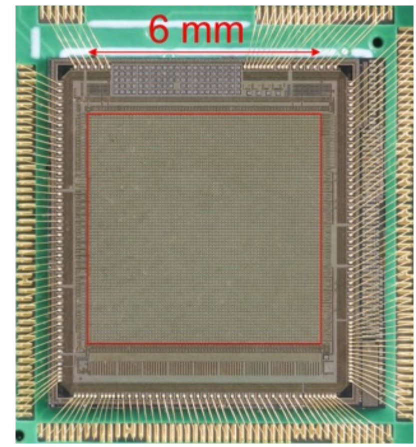
- D^3
- GEM for charge multiplication
- ATLAS FE-I3 (FE-I4) chip for readout
- 50X400μm (50X250) pixel size

Topmetal CMOS charge sensor



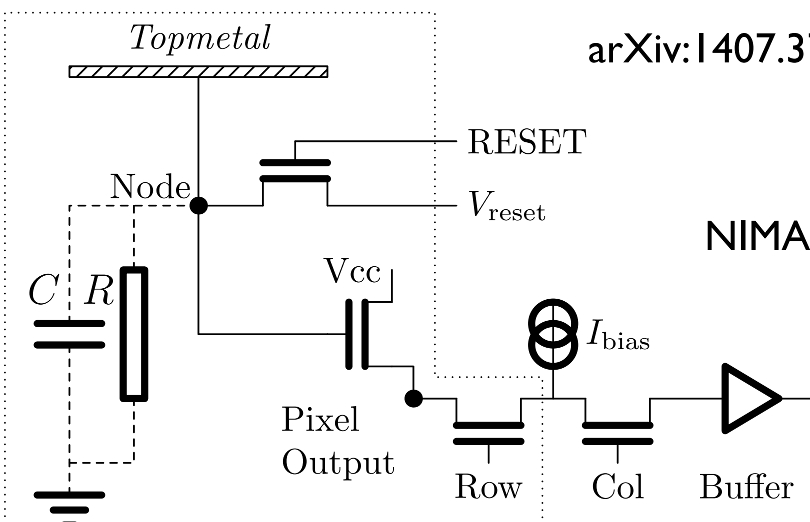


- XFAB XH035 Process
- ~80µm pixel size



Topmetal-I

- Produced in 2012, validated in 2013
- Direct voltage readout
- High analog bandwidth



arXiv:1407.3712

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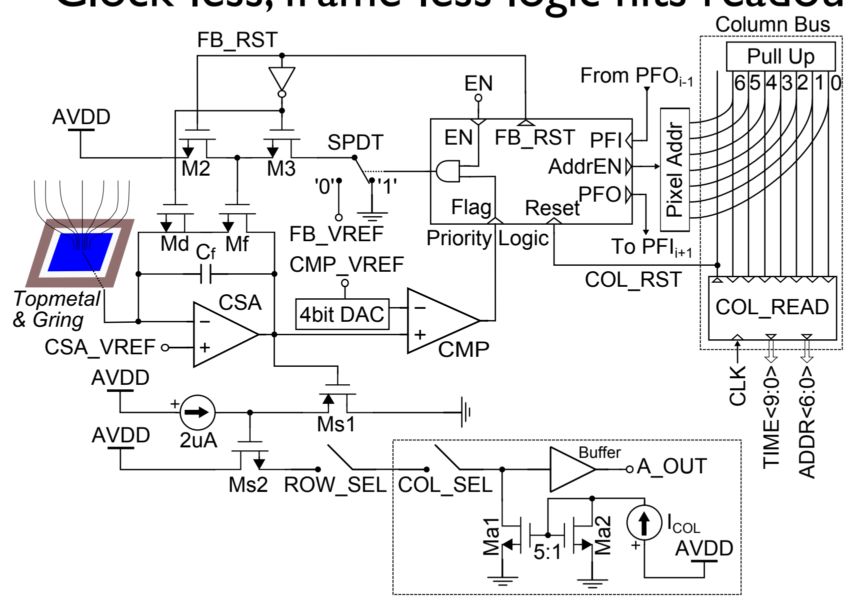
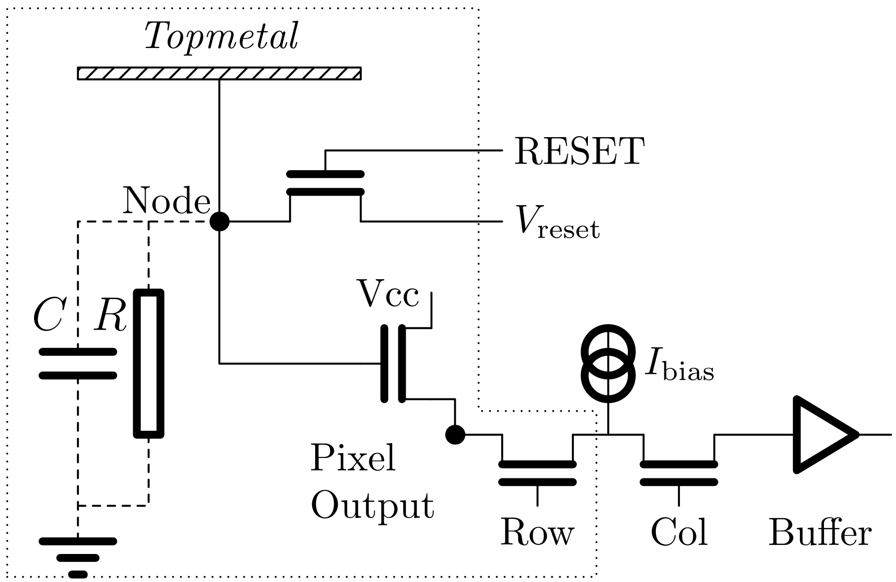
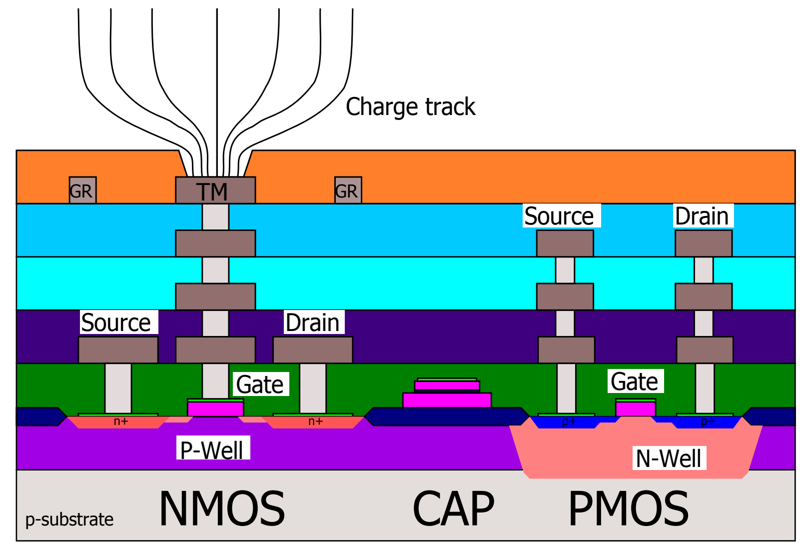
Topmetal-II⁻

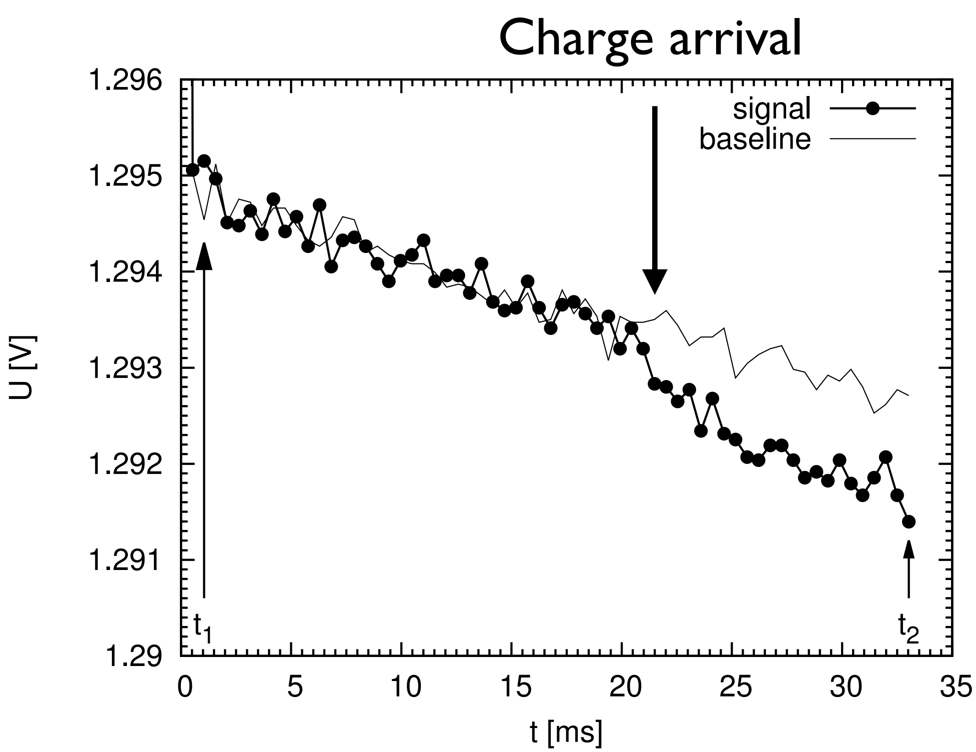
- Produced in 2014, validated in 2015
- Charge sensitive amplifier, <15e- noise
- Clock-less, frame-less logic hits readout

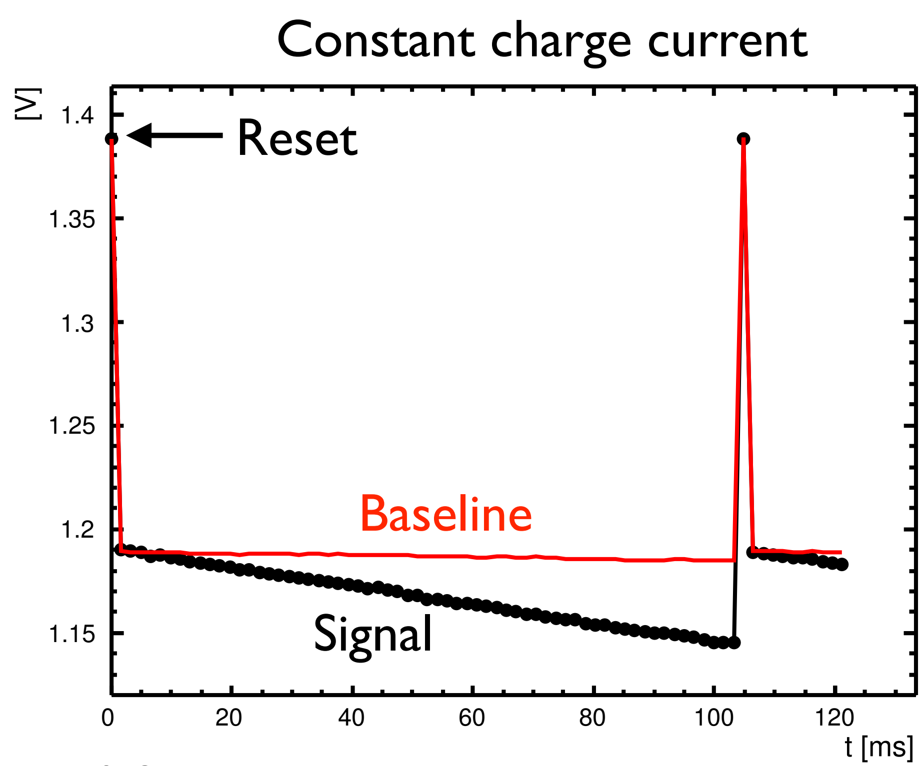


Topmetal-I (2012)



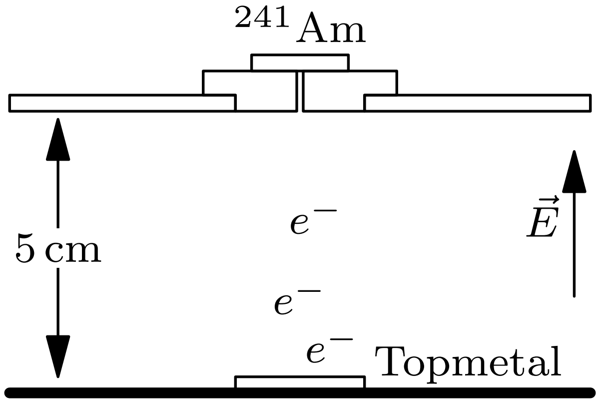


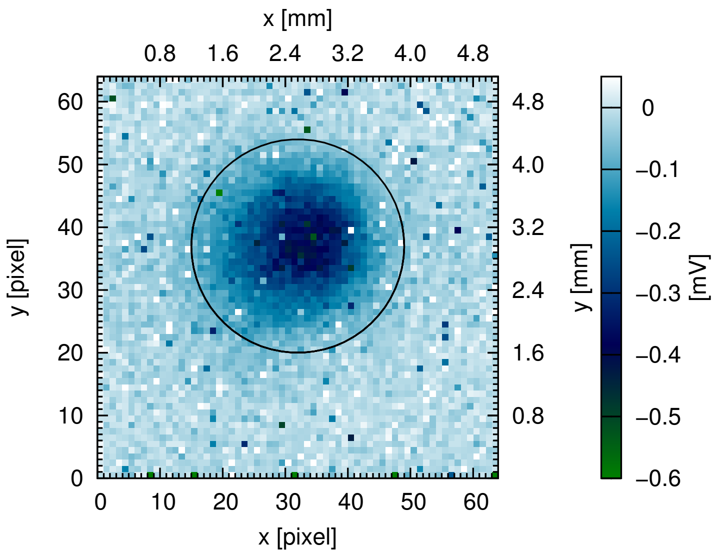


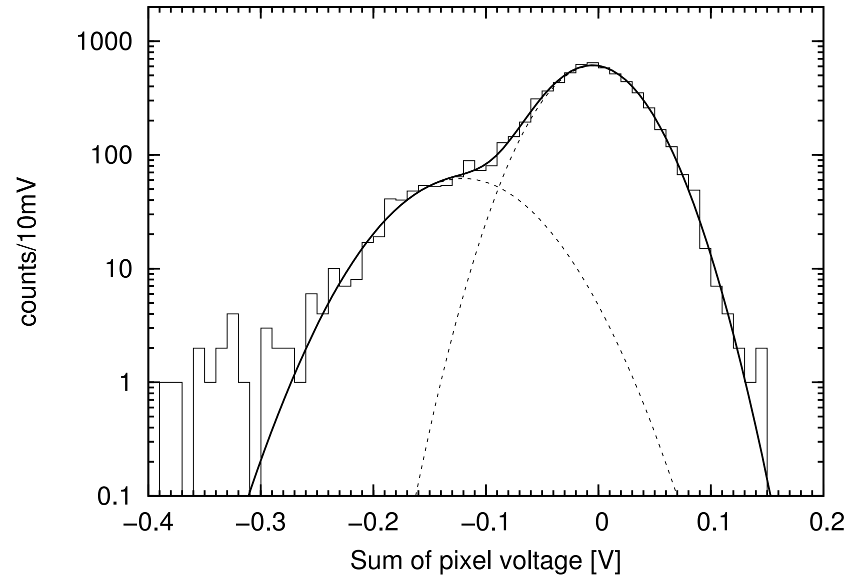


C≈210fF, 1electron causes 0.8μV voltage drop

Single alpha events from ^{241}Am in air

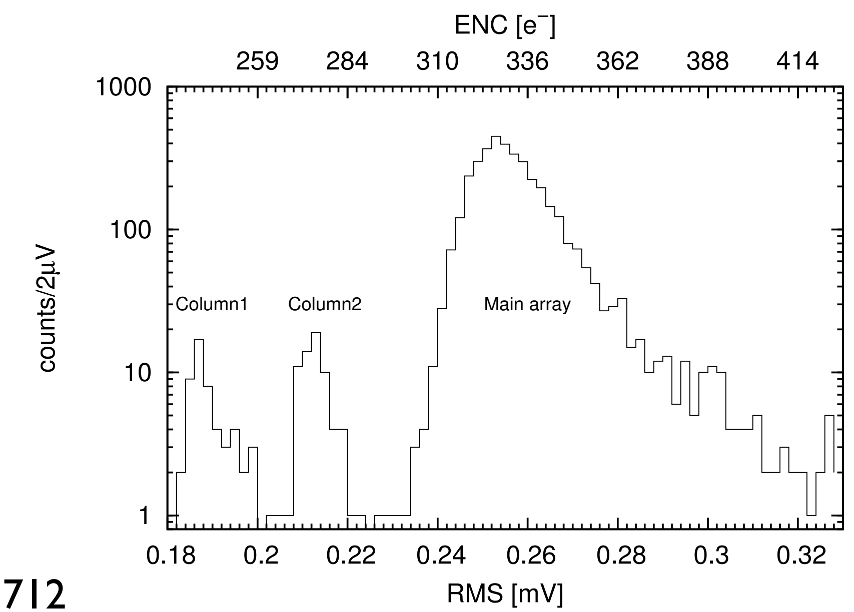






$\chi^2/\mathrm{NDF} = 53.8/60$

Single-alpha peak at (-0.120 ± 0.008) V



5.45MeV alpha

W-value of air is 35eV

1.56X10^5 e$^-$/ion pairs per event

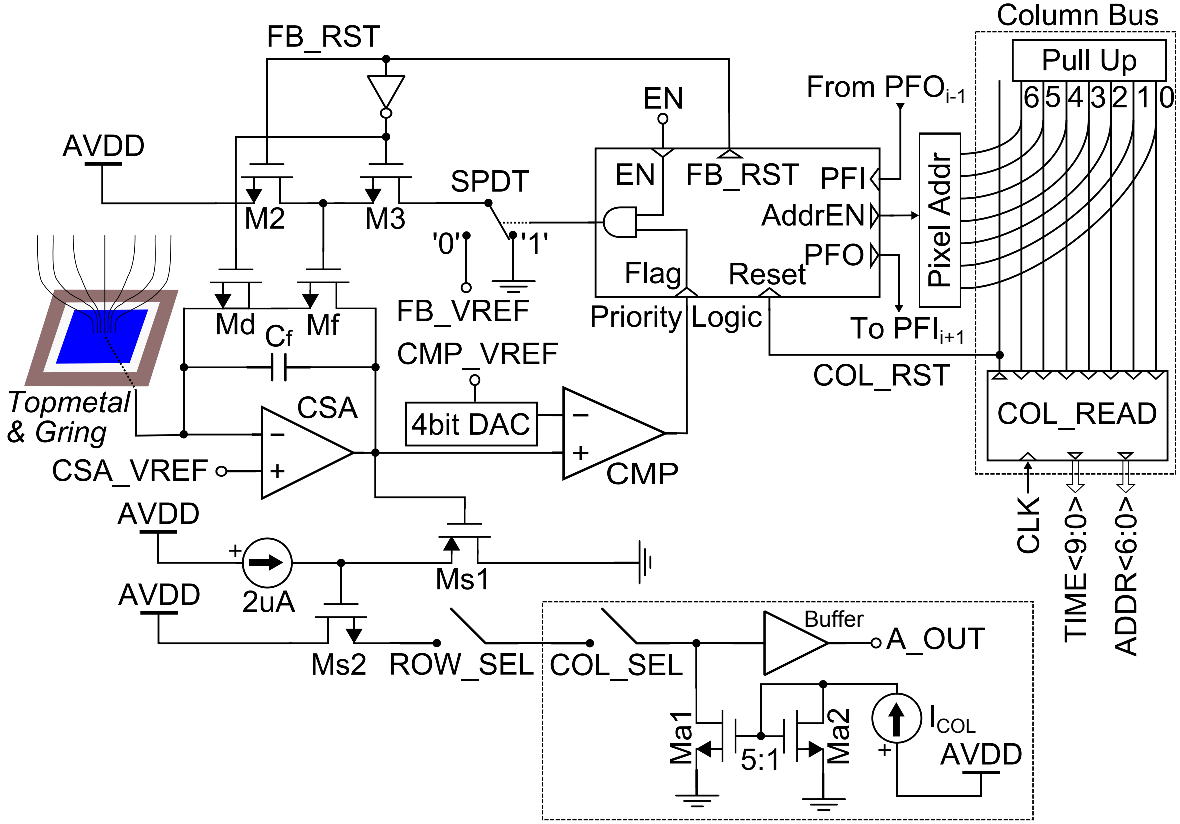
C=207fF, 12% uncertainty

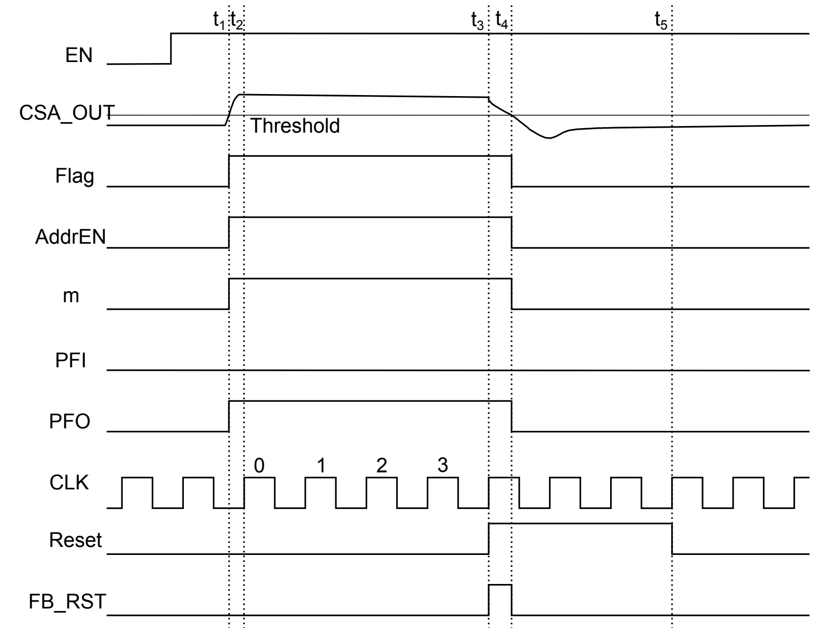
Most probable ENC=330 e-

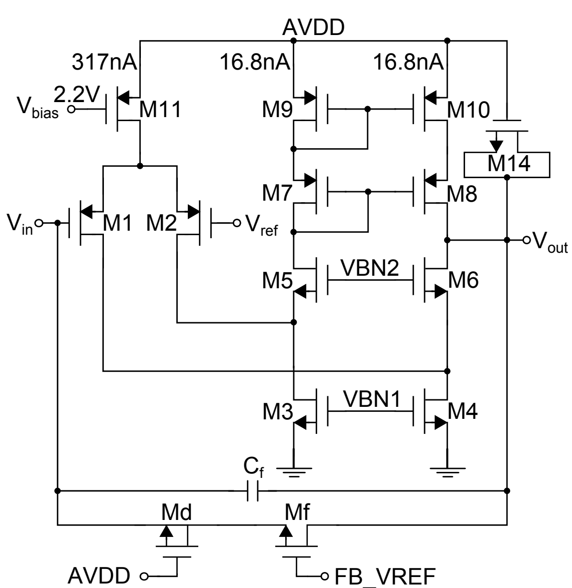
$N_e = \sqrt{k_B T C} \approx 190 e^-$ when $C = 210\,\mathrm{fF}$

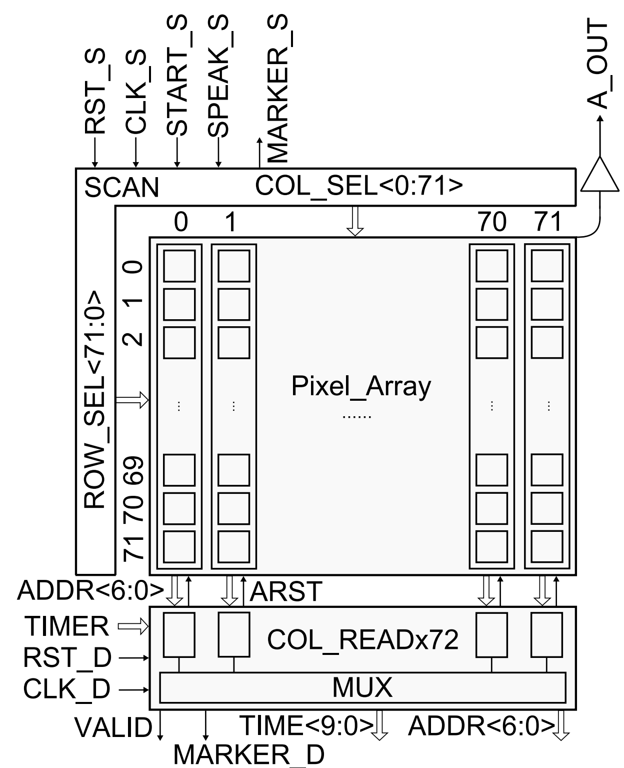
arXiv:1407.3712

Topmetal-II⁻ (2014)

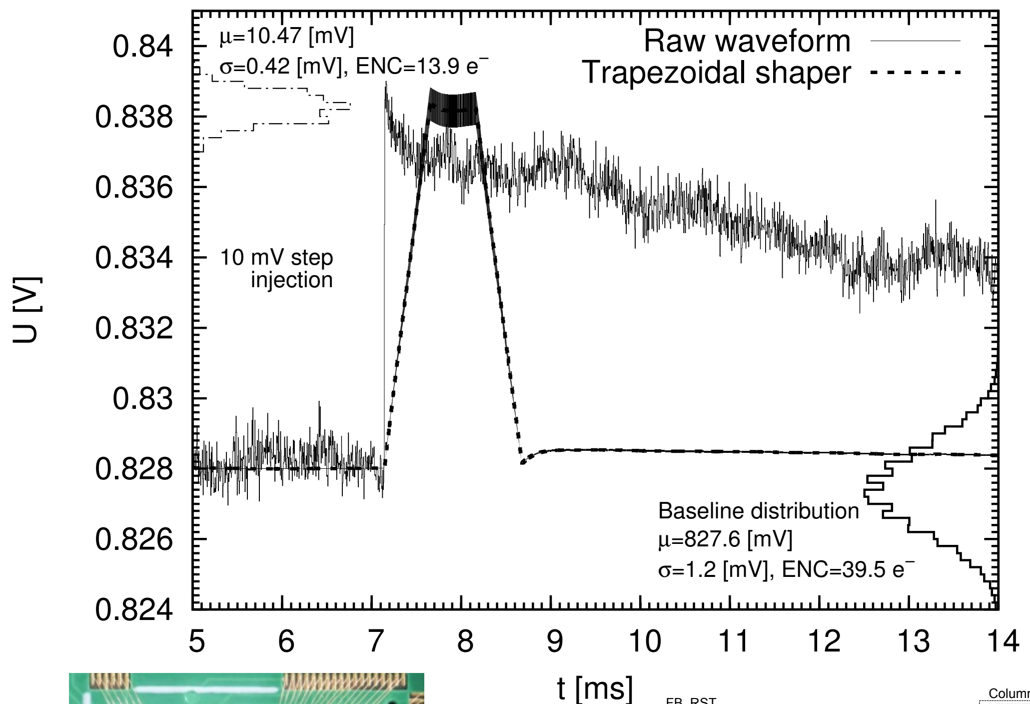


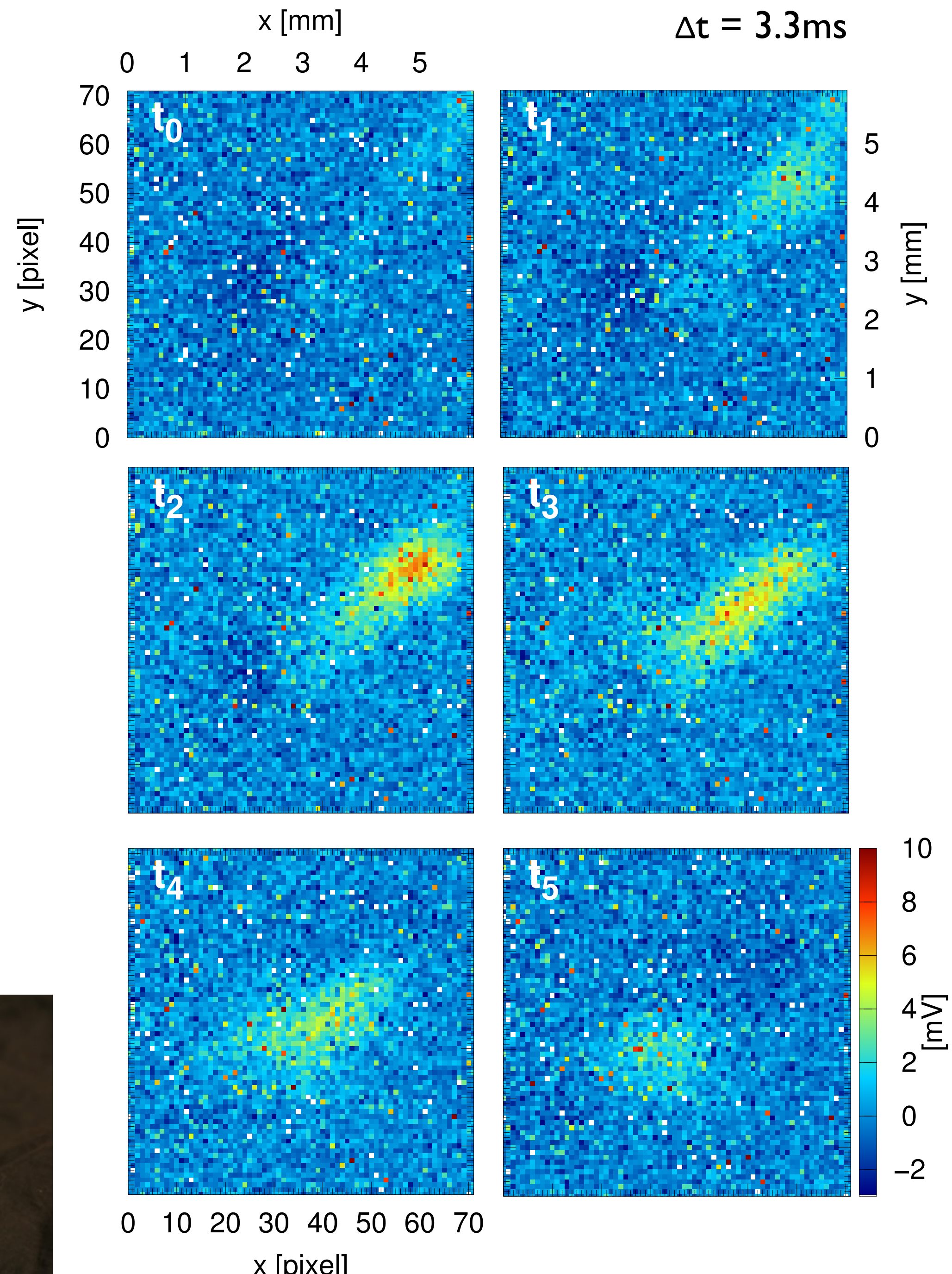


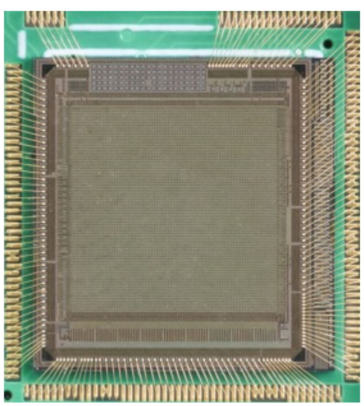


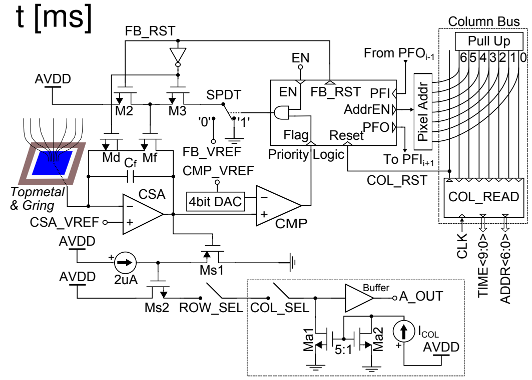


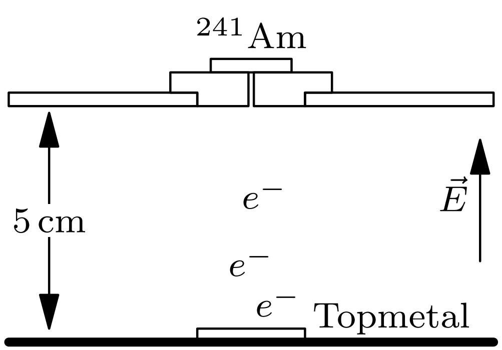
Topmetal-II⁻ seeing alpha tracks in air

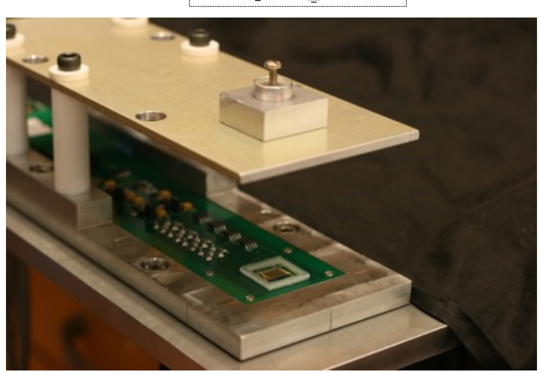












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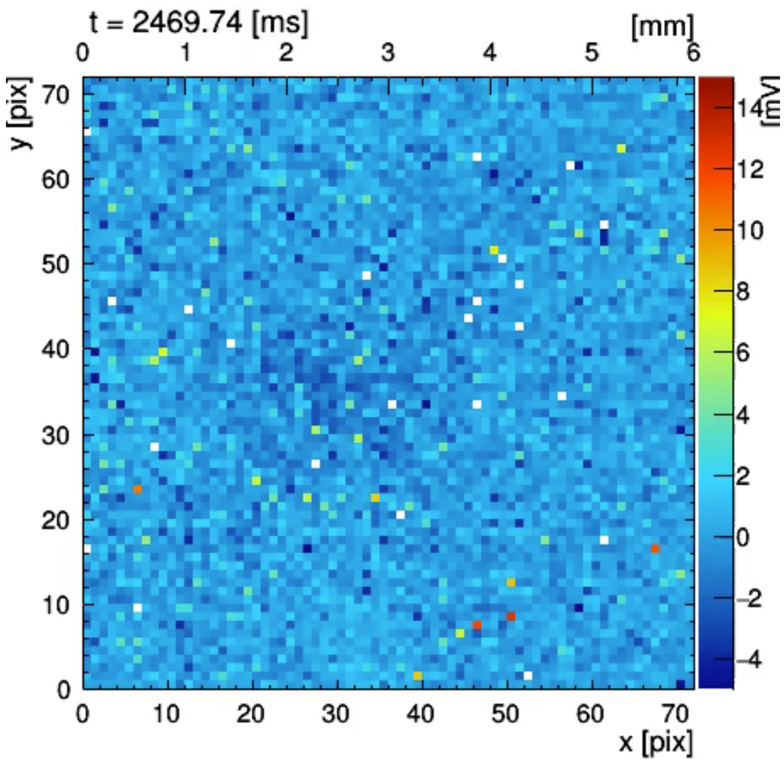
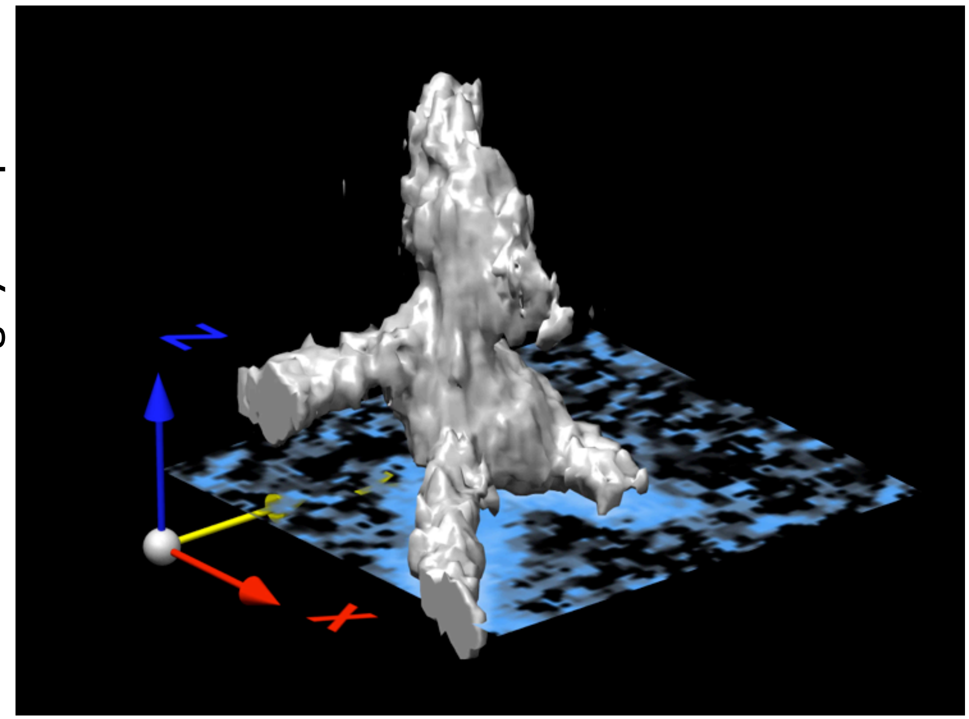
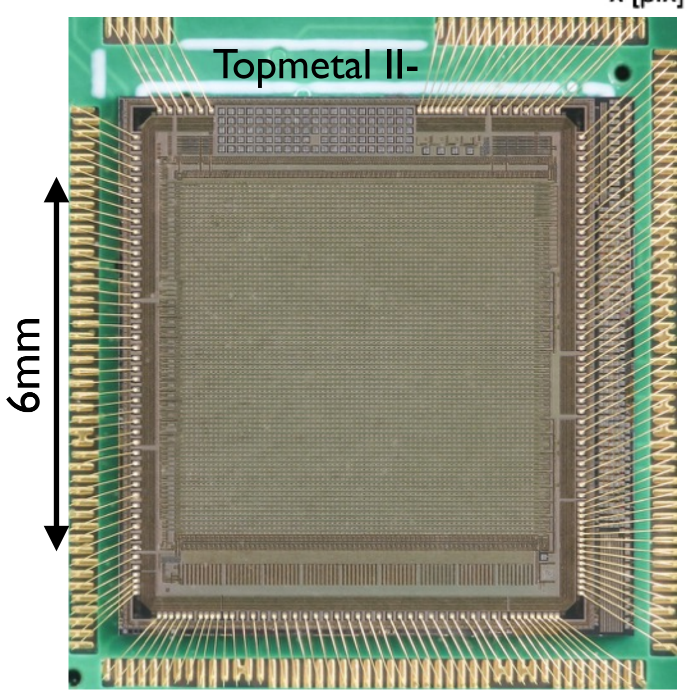
Charge Distribution Reconstruction without Gas Gain

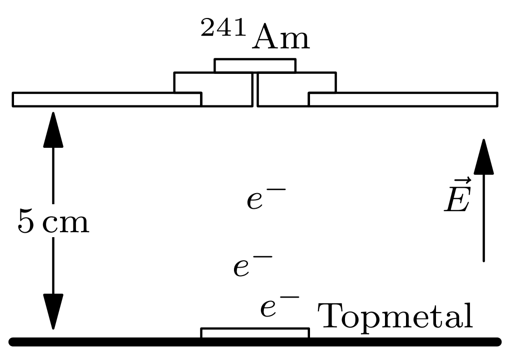


Z dimension is highly compressed

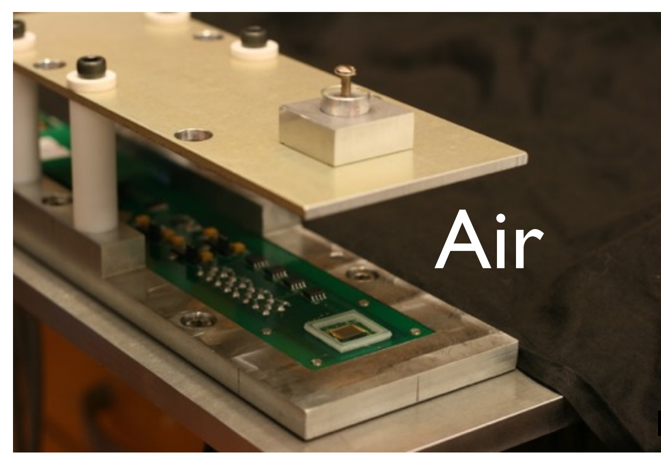




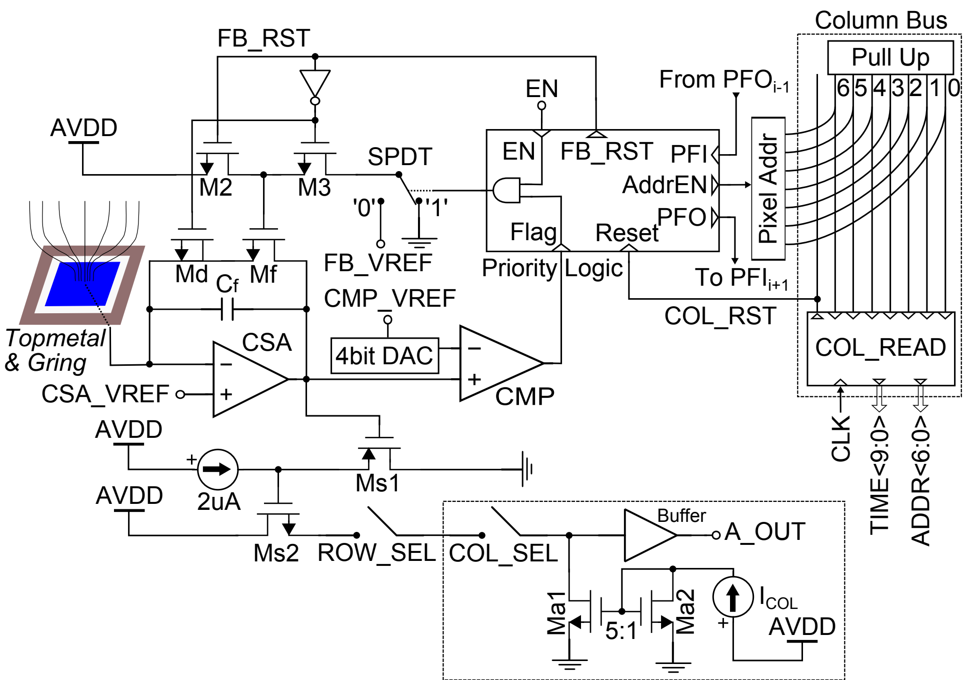
- *Topmetal* CMOS sensor: 80X80μm pixel size
- Direct charge collection
- Standard 0.35μm CMOS process, no post-processing

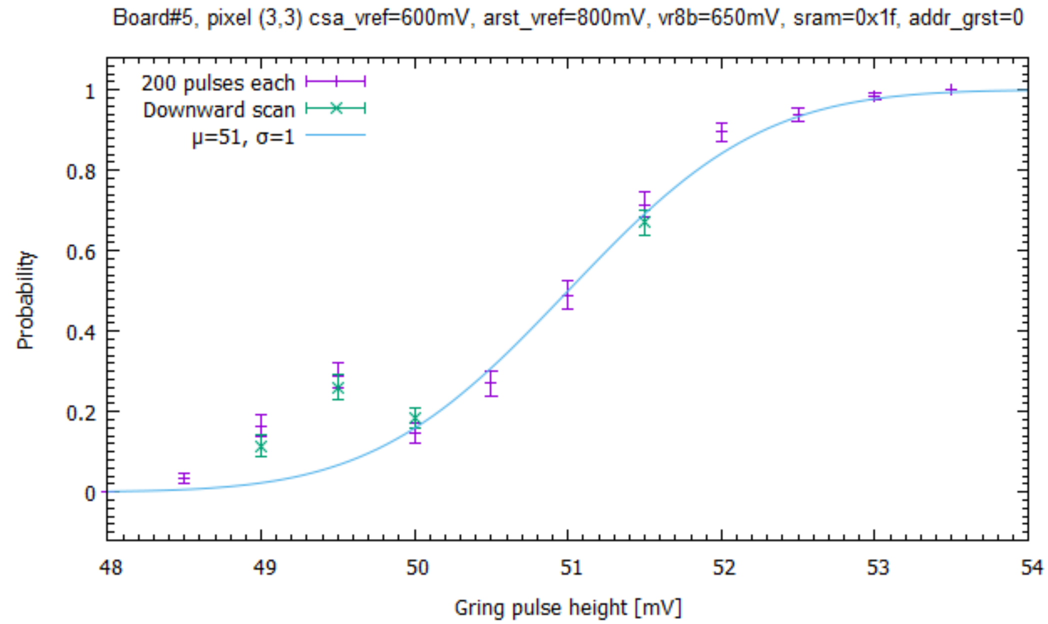


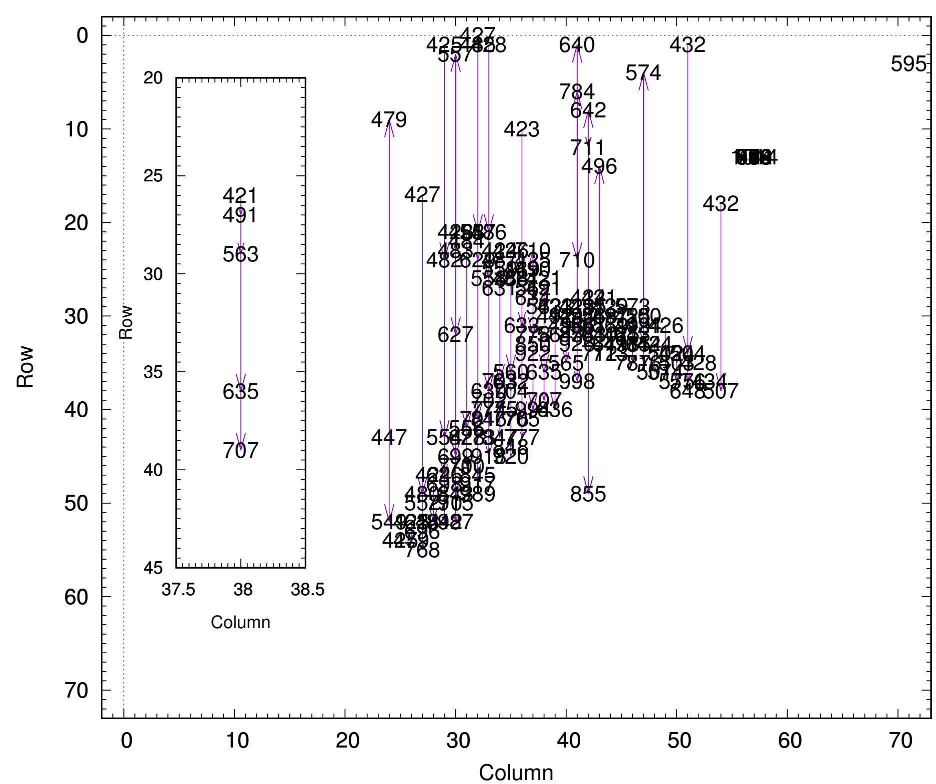
Time Projection Chamber (TPC)



Digital readout of *Topmetal-II⁻*





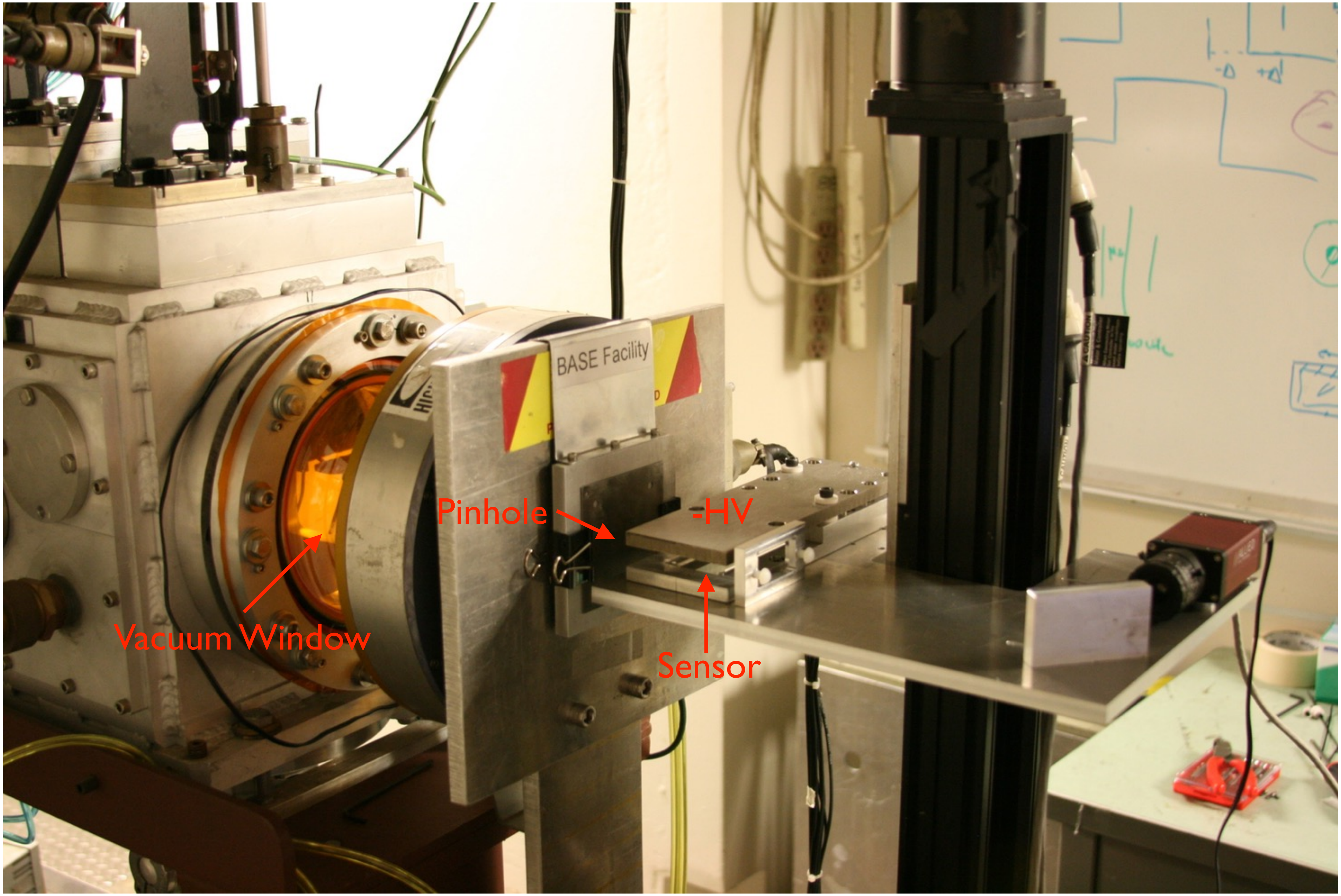


Column-based priority logic

arXiv:1608.06399

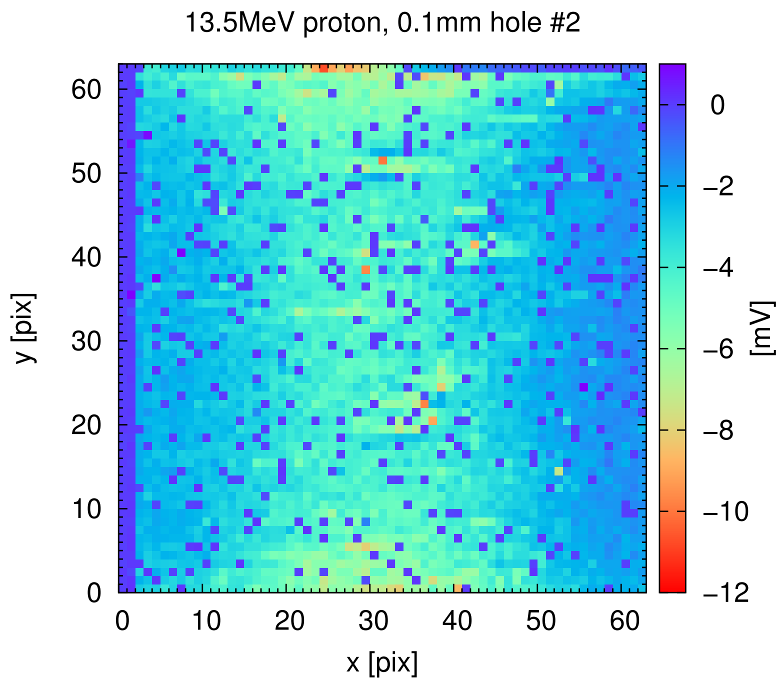
Applications

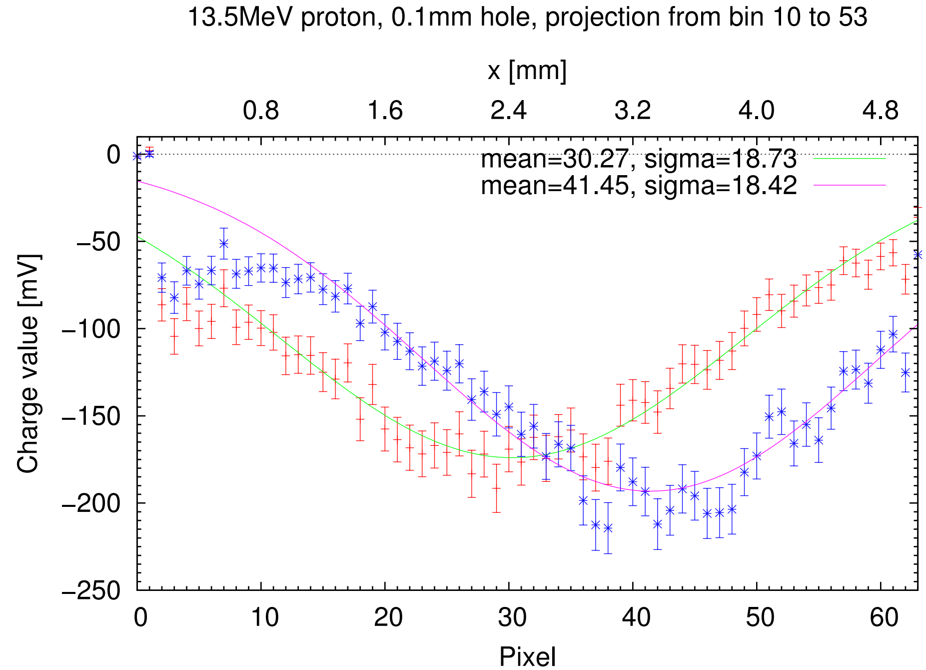
Proton Beam Positioning

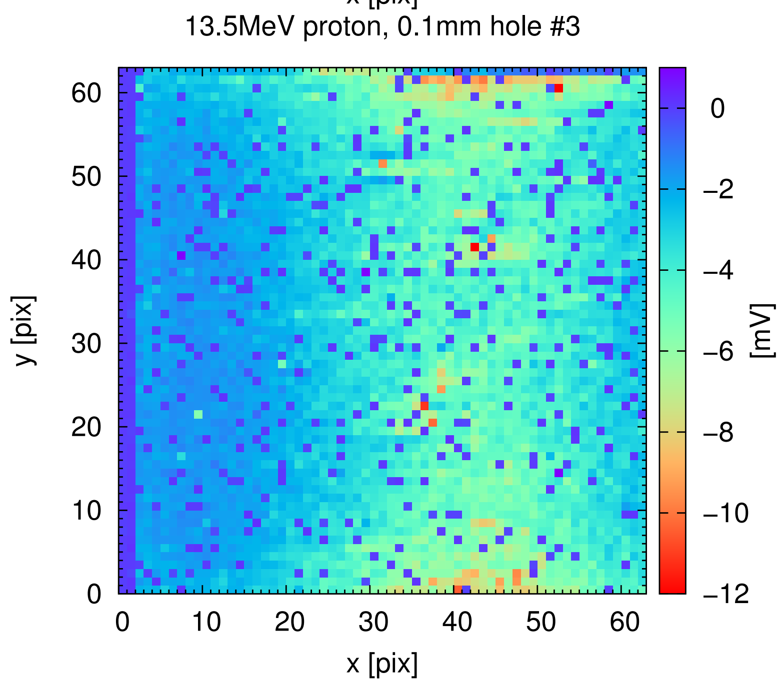


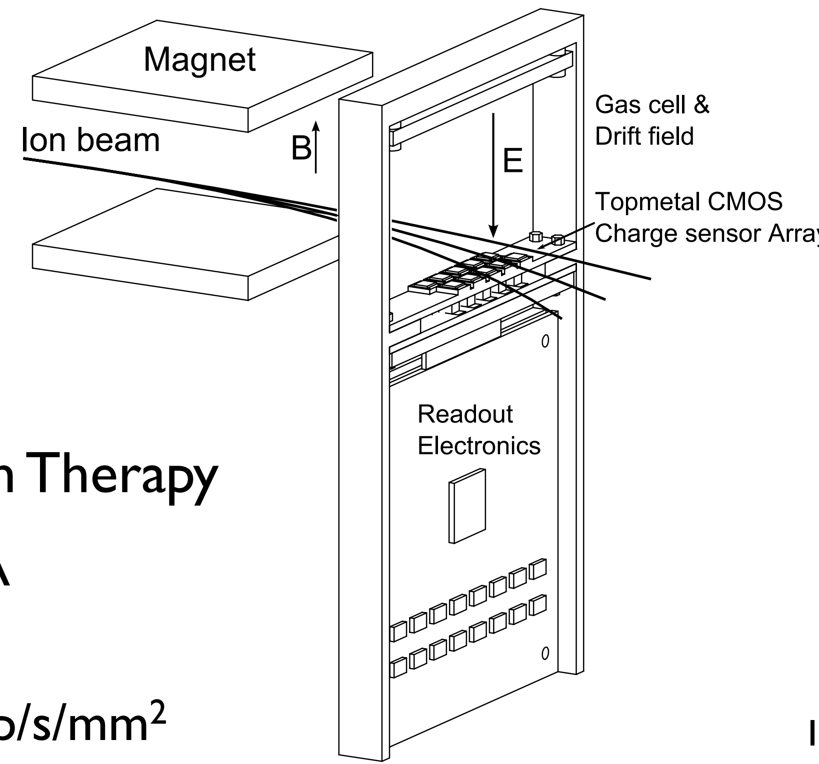
13.5MeV proton beam from the 88-inch Cyclotron, 20E6 p/s/mm^2

Proton Beam Positioning





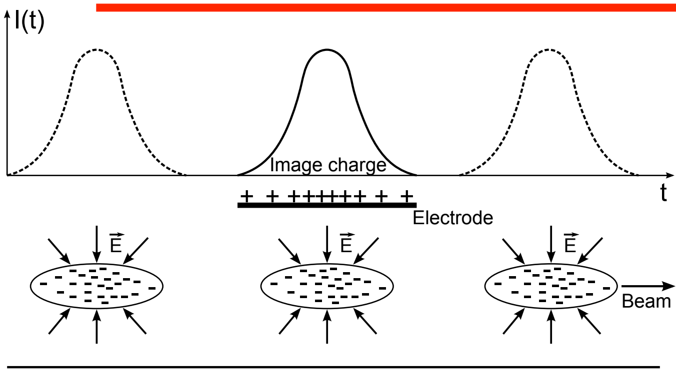


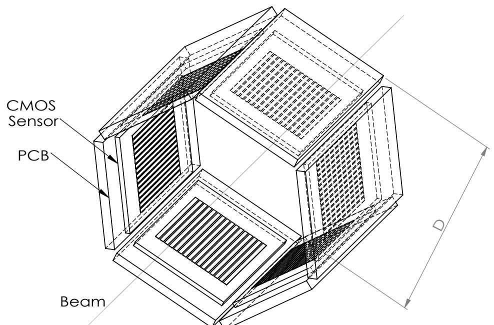


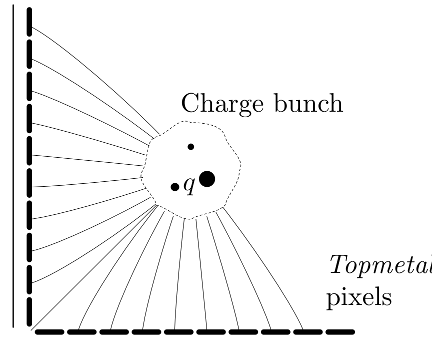
- Proton Therapy
- BELLA

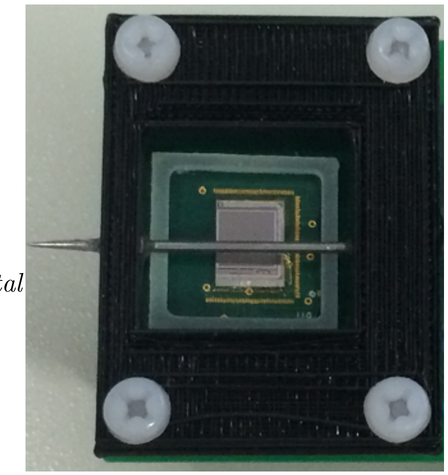
13.5MeV proton beam from the 88-inch Cyclotron, 20E6 p/s/mm^2

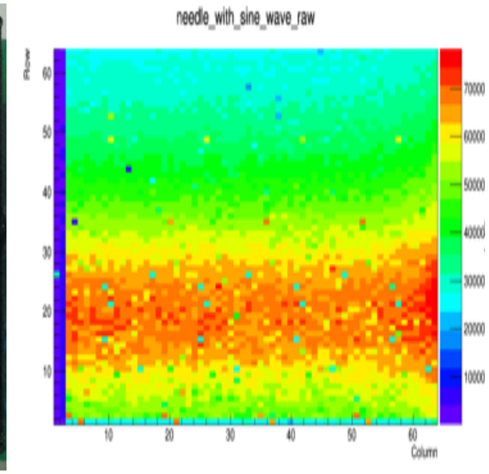
Beam Distribution Tomography



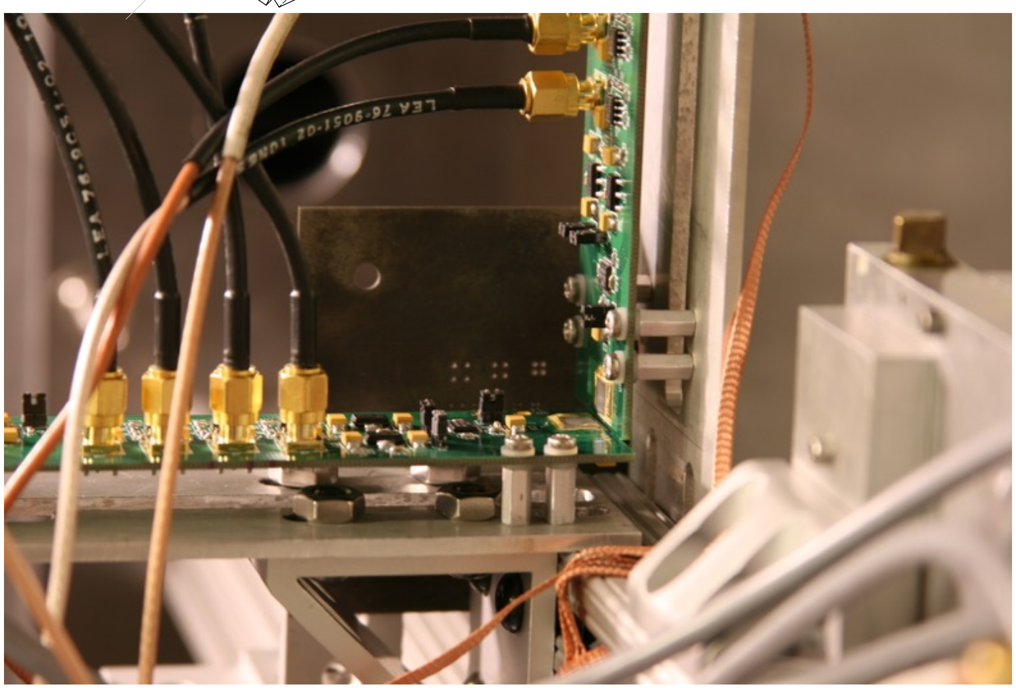




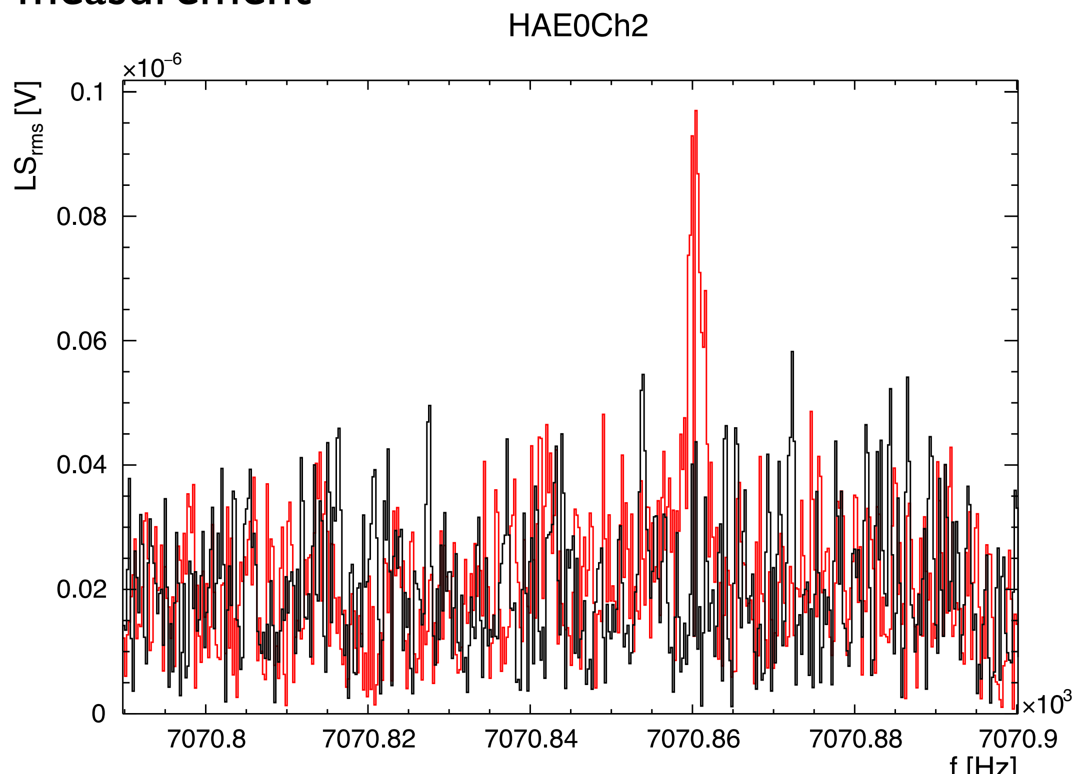




Non-disruptive beam measurement

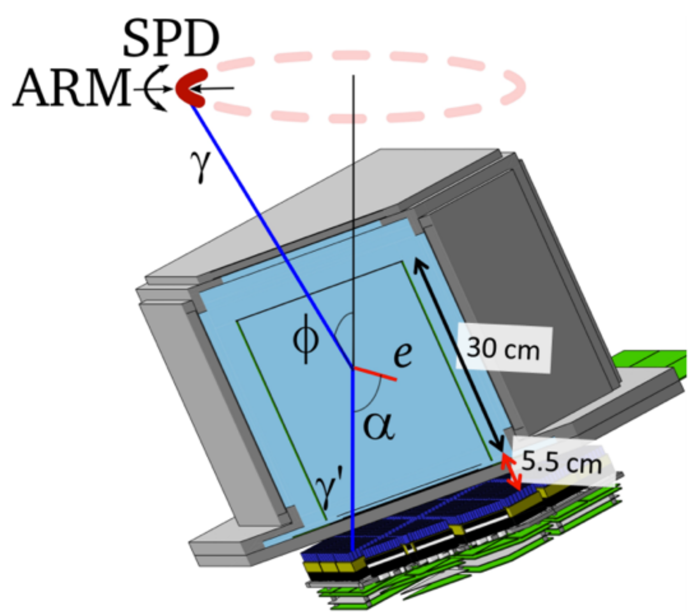


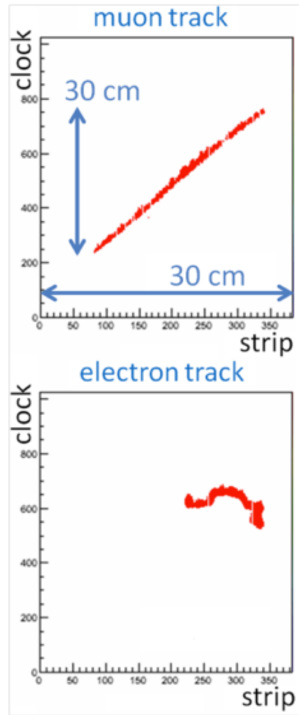
Heavy ion run setup in Cave 4B of 88 Cyclotron (in vacuum)



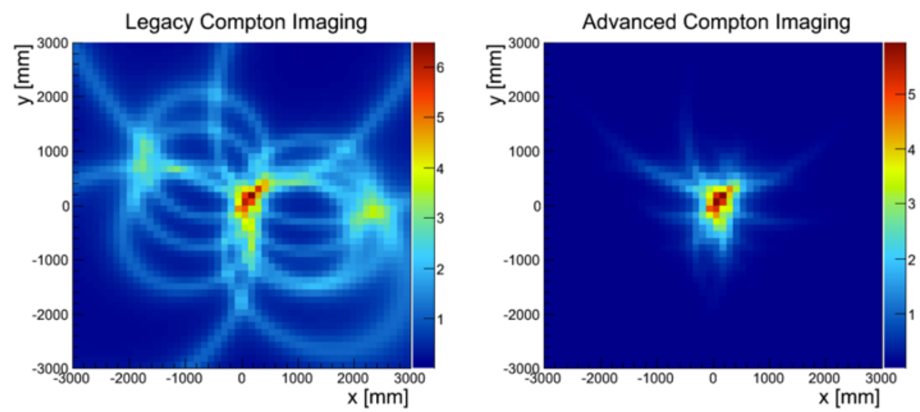
1 electron ~ 0.8μV

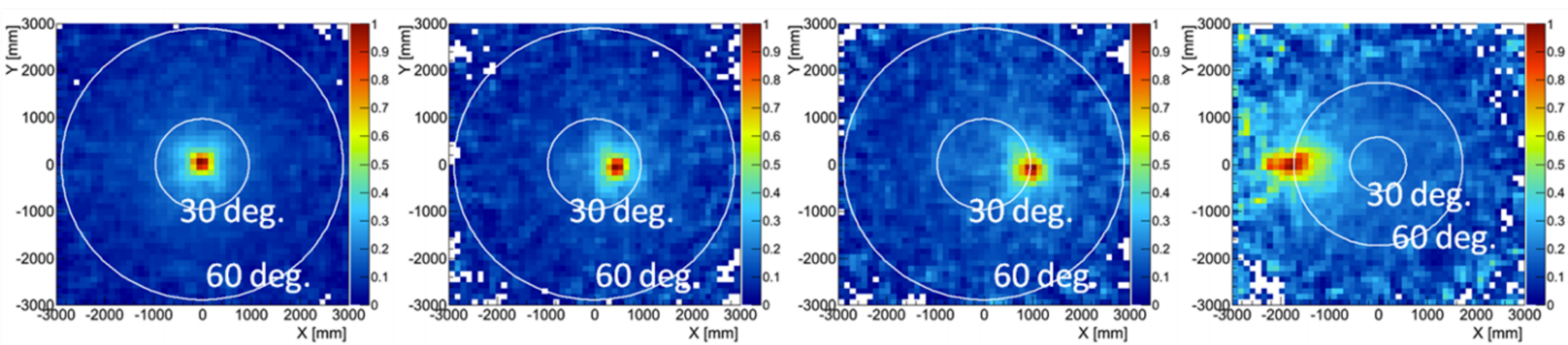
Electron-track Compton Imaging





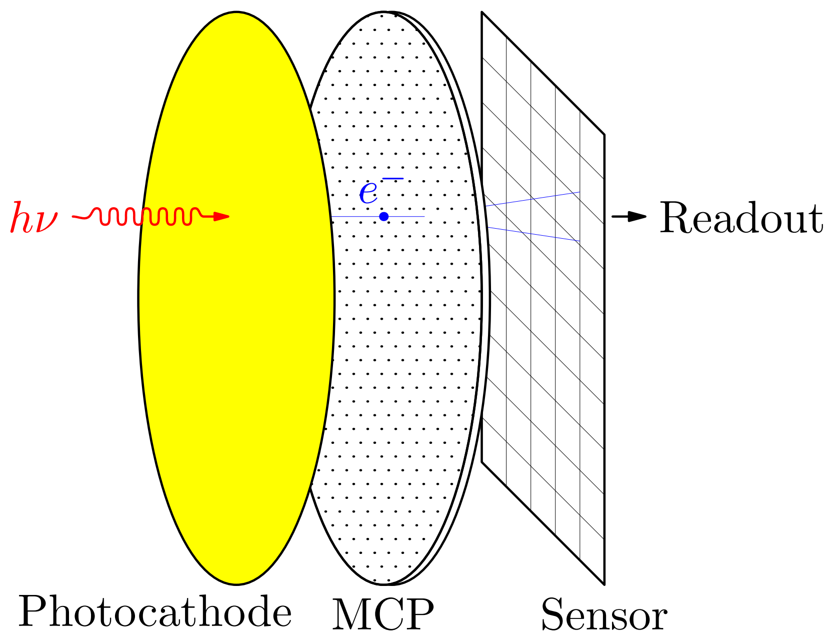
- Medical Imaging
- Gamma (X-ray) Astronomy

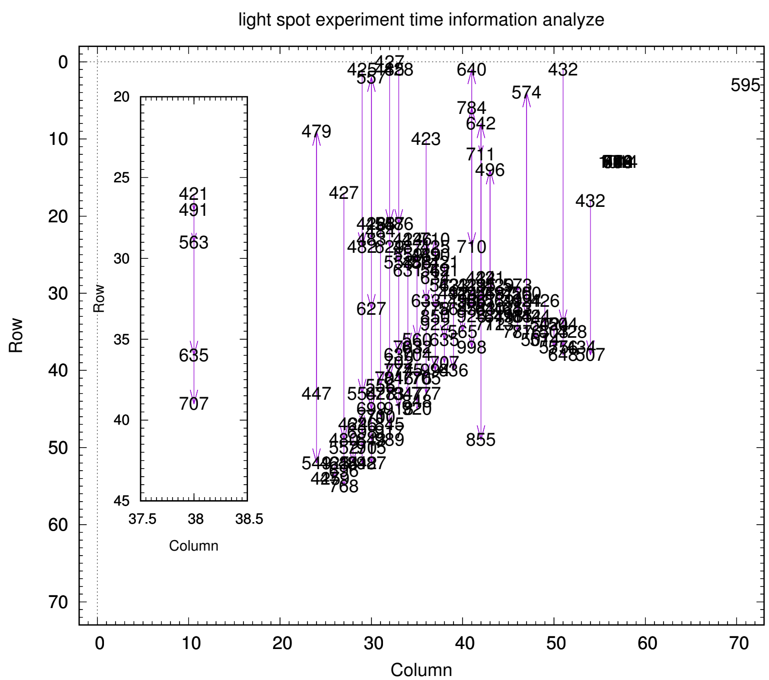


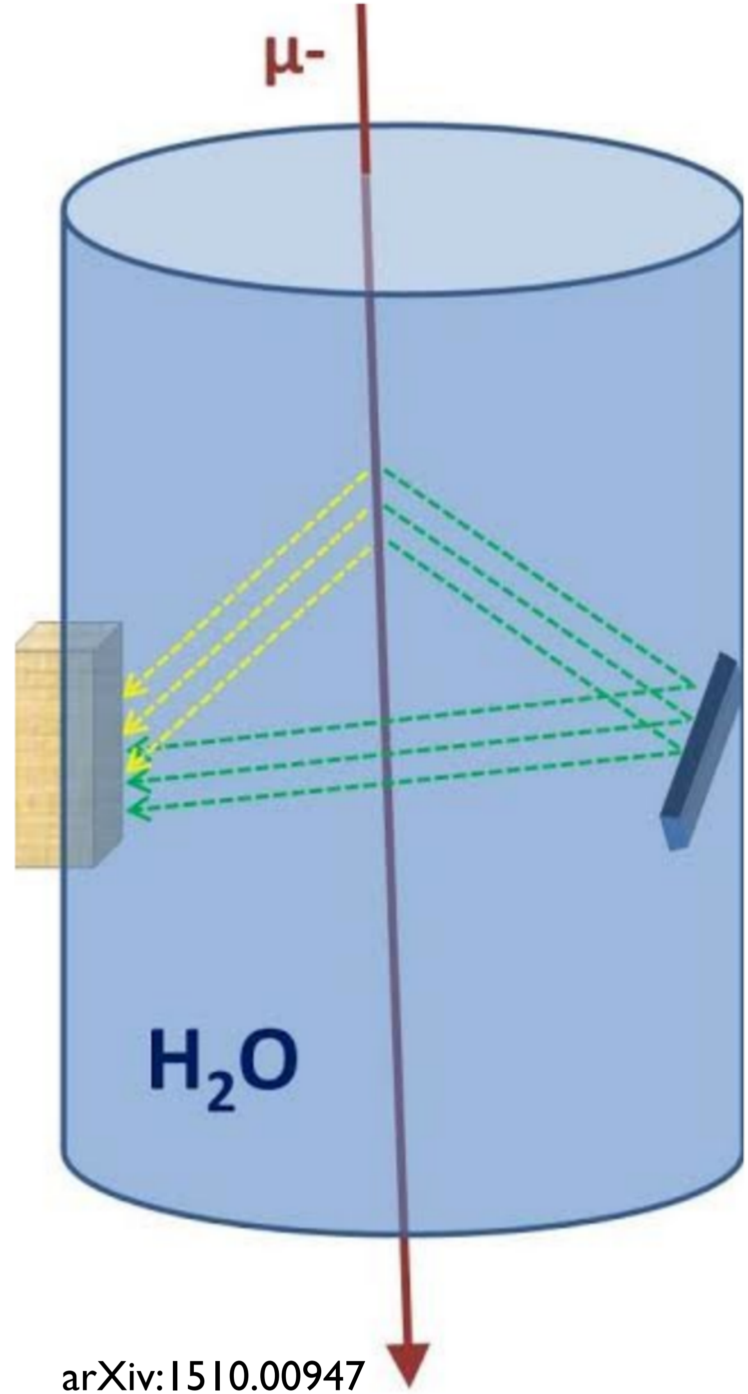


Simulations from SMILE, ETCC, arXiv:1312.0438

Fast photon detector & optical TPC

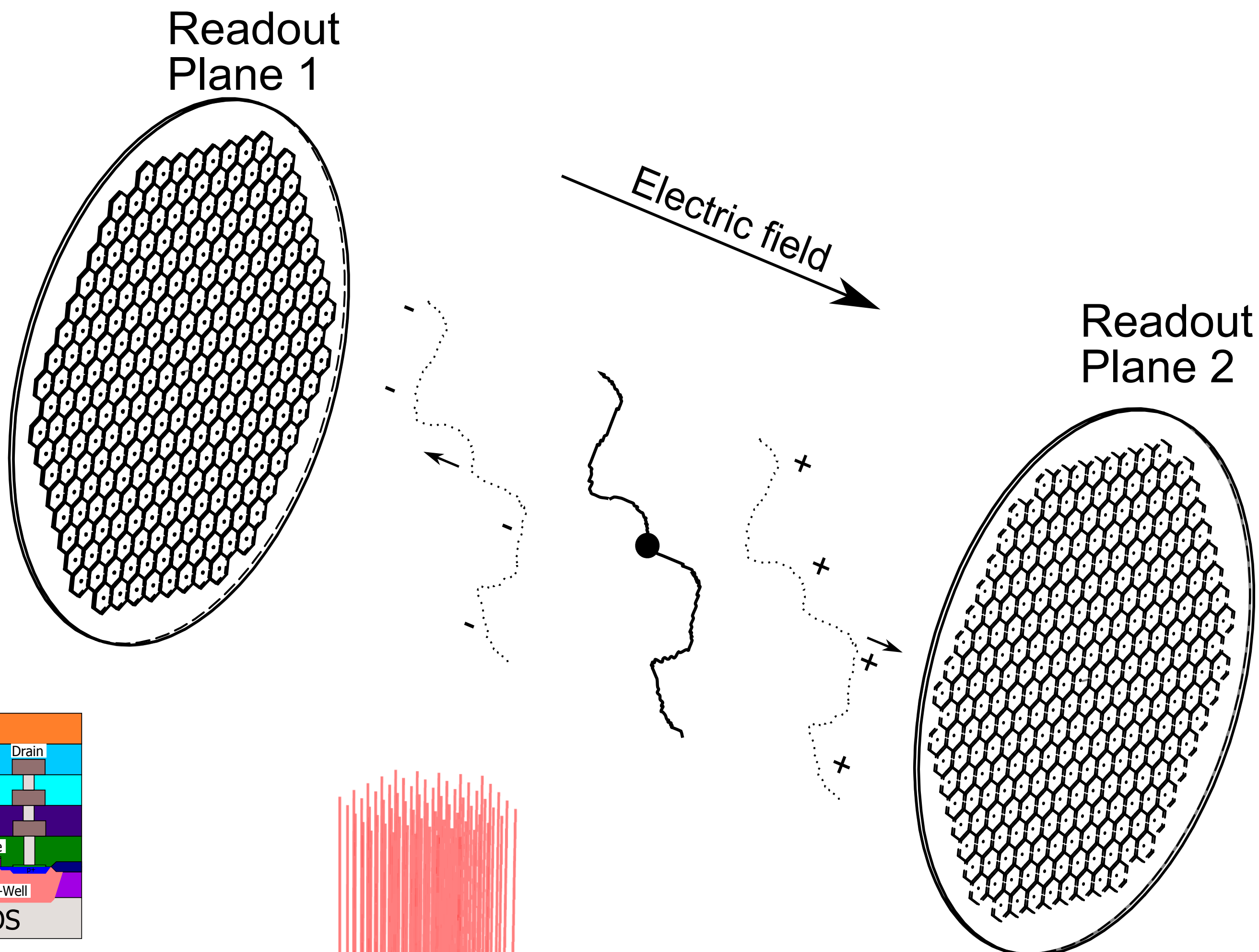


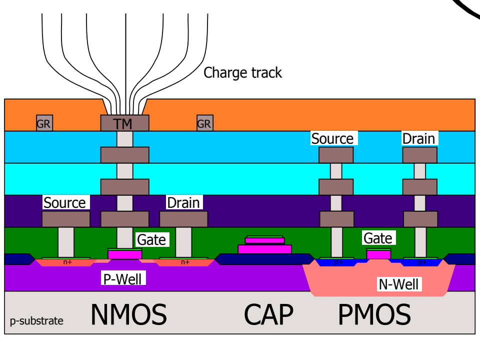


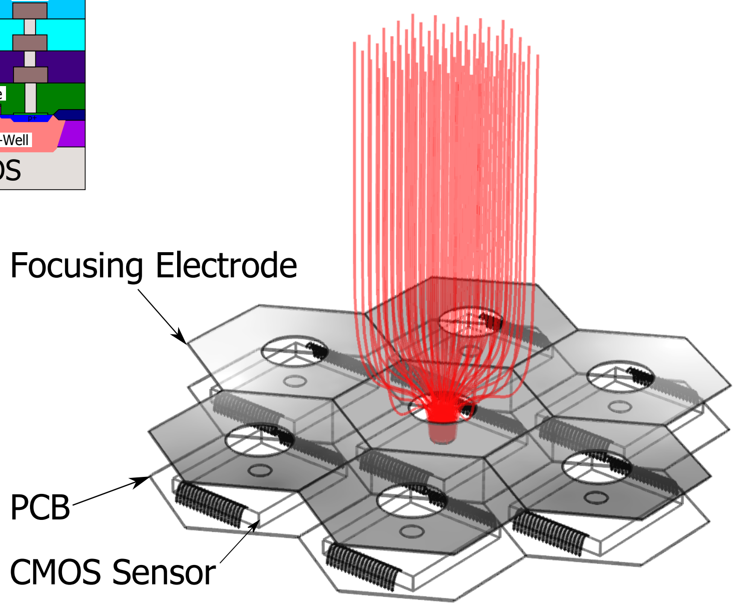


arXiv:1510.00947

Topmetal CMOS charge sensor array for TPC

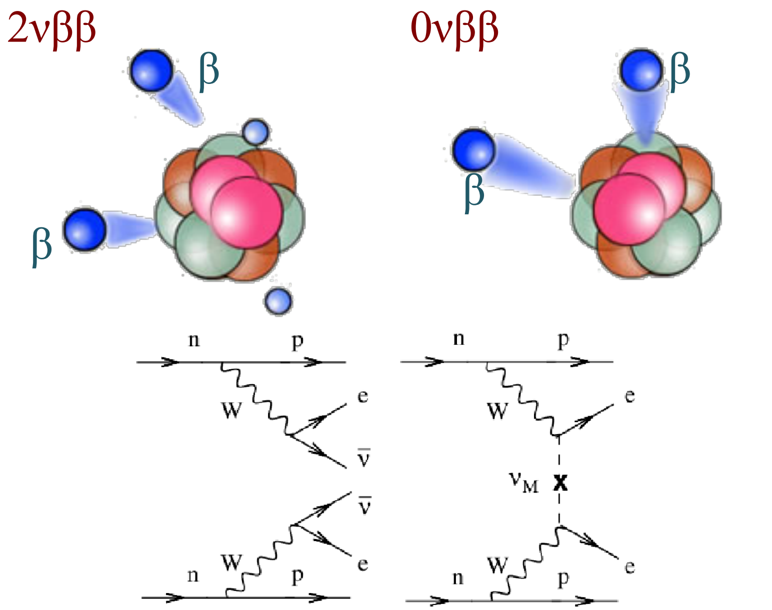


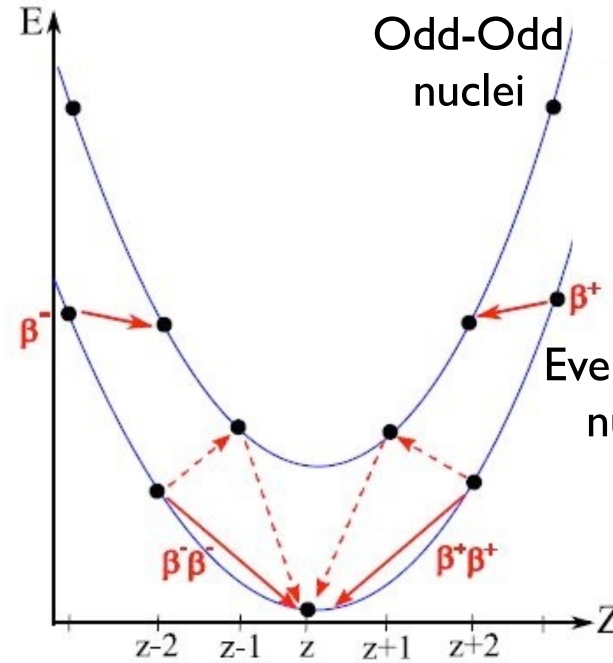




- Eliminate charge amplification
- Direct charge collection in X-Y
- Z is determined by the +/- charge arrival time difference

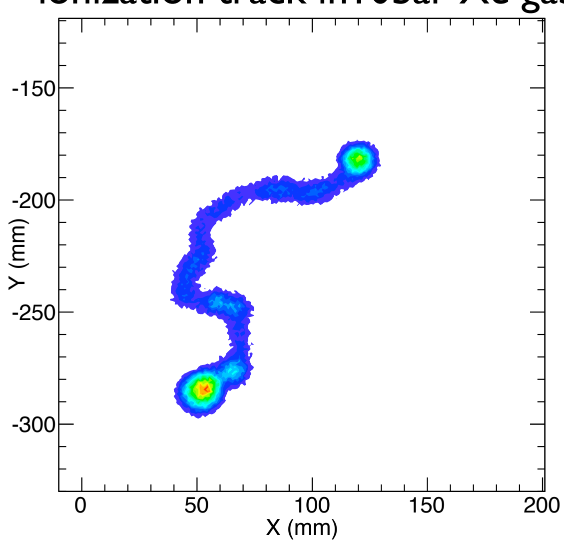
Physics Motivation: Neutrinoless Double-Beta Decay

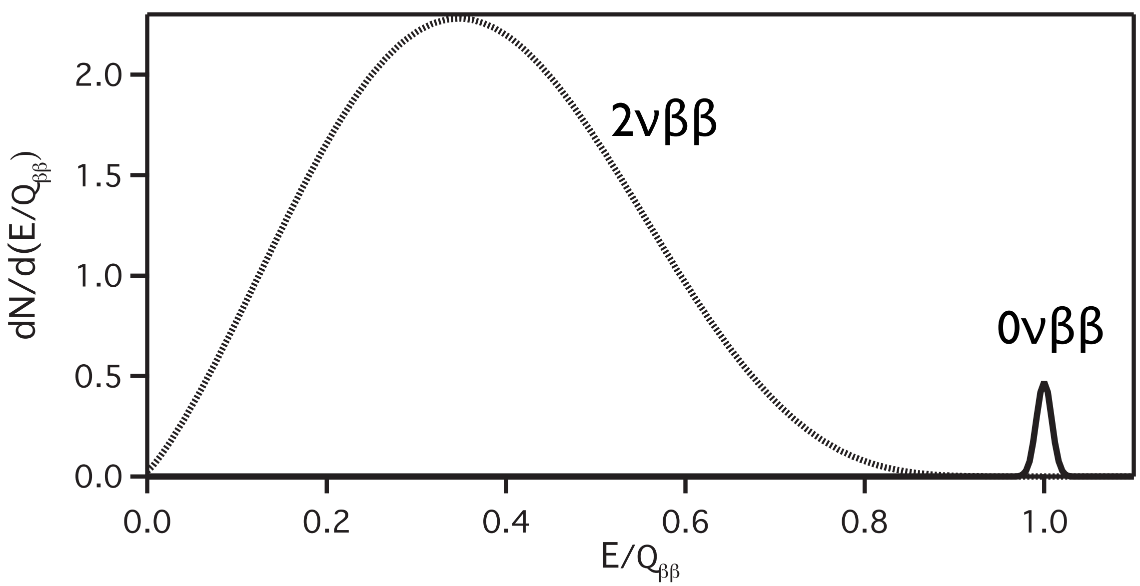




half-life sensitivity $\propto a \cdot \epsilon \sqrt{\dfrac{M \cdot t}{b \cdot \delta E}}$

Simulated ^{136}Xe 0νββ event,
ionization track in10bar Xe gas



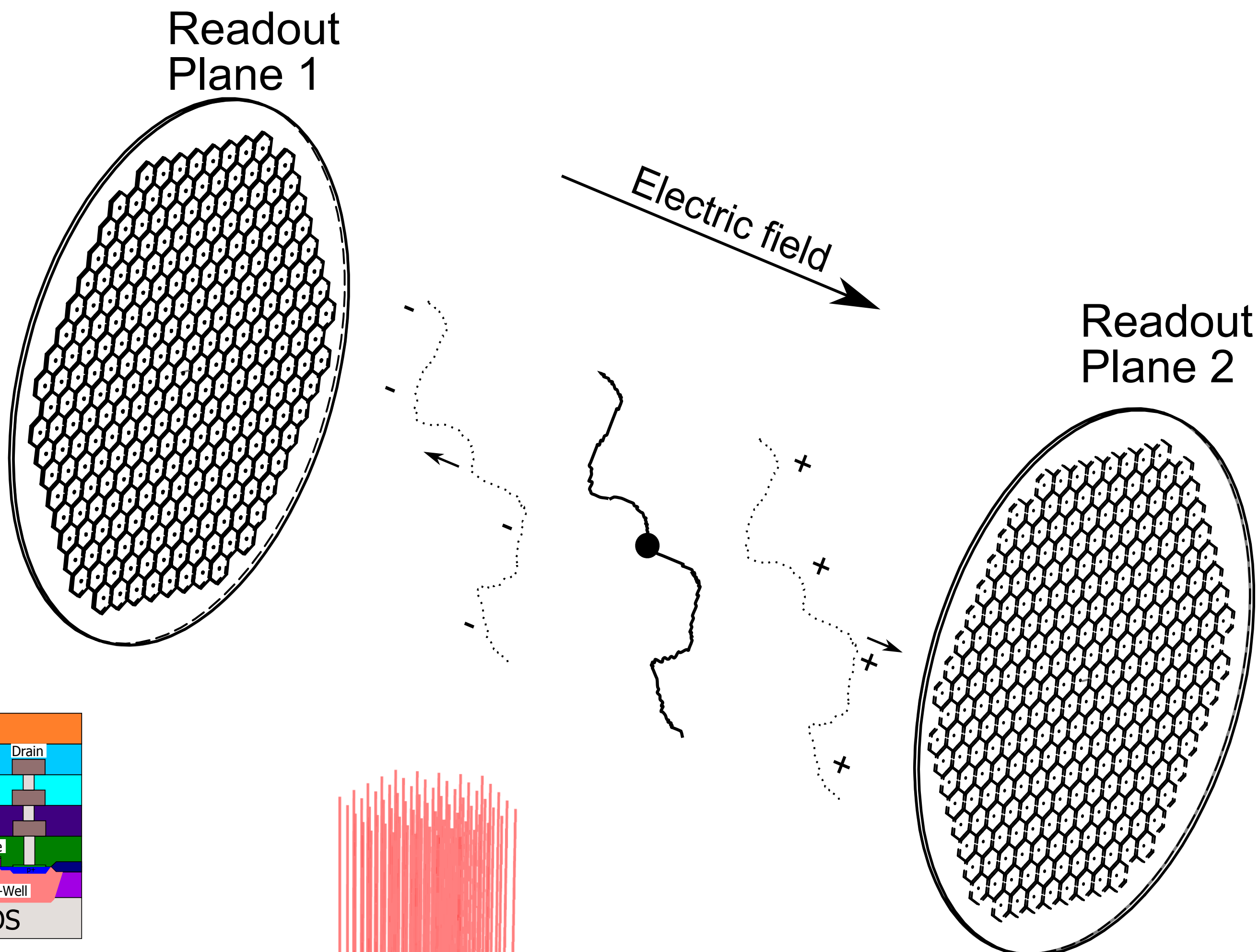


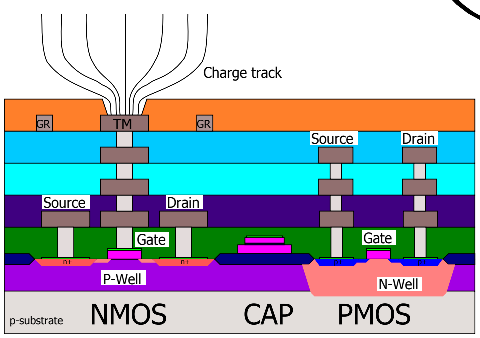
Assumes BR 0ν/2ν = 1% and detector energy resolution is 2%

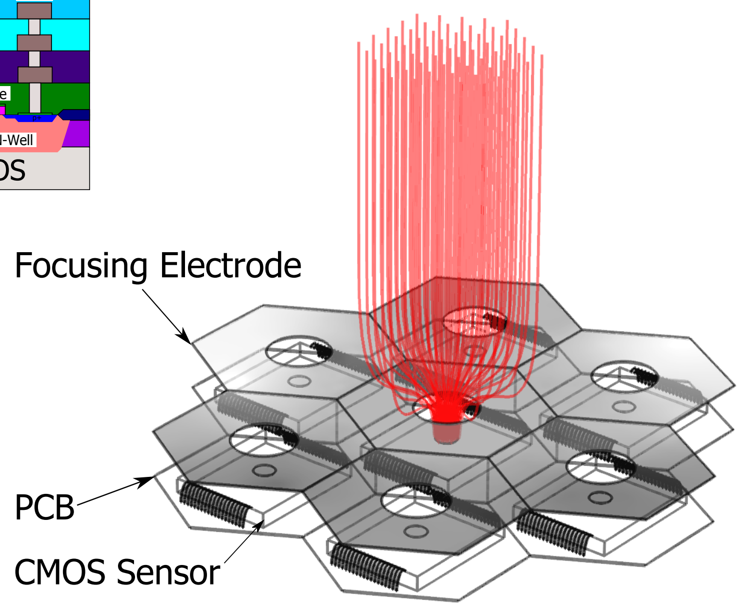
Challenges and solutions

- Scalable to large mass while maintaining:
  - Excellent energy resolution at $Q_{\beta\beta}$
  - Background control
  - Geometrical signature of decay (positive signal identification)
- High pressure gaseous TPC
  - HP Xe has been proven to have excellent intrinsic energy resolution (ionization statistics)
  - NEXT readout scheme: electroluminescence achieved high energy resolution. Leaves room for improvements in radio-purity and charge track reconstruction
  - HP SeF_6 provides better geometrical signature, and provides an alternative $0\nu\beta\beta$ isotope ^{82}Se for verification

Topmetal gainless charge readout for 0νββ



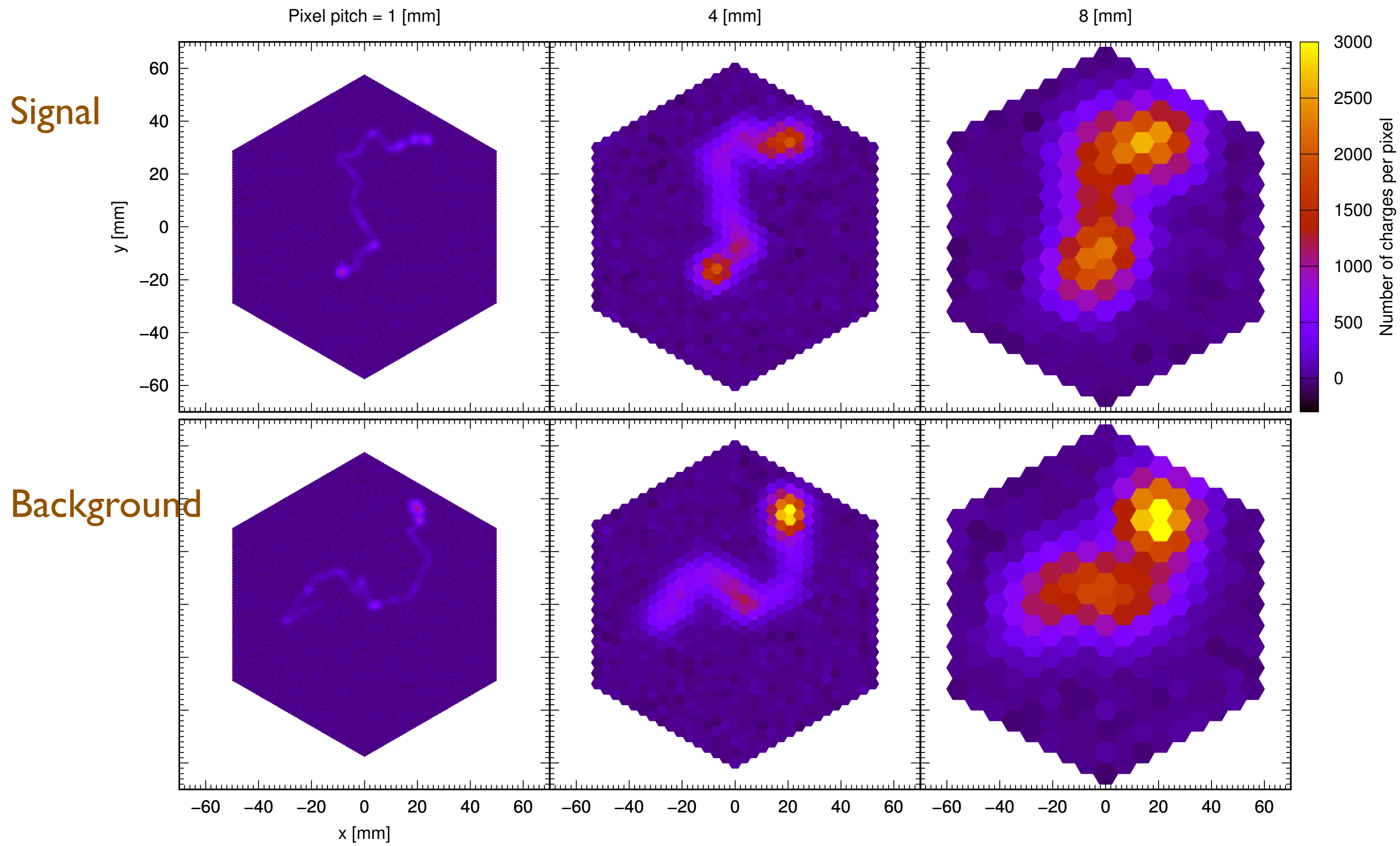




- Eliminate charge amplification
- Direct charge collection in X-Y
- Z is determined by the +/- charge arrival time difference
- R&D supported by LDRD

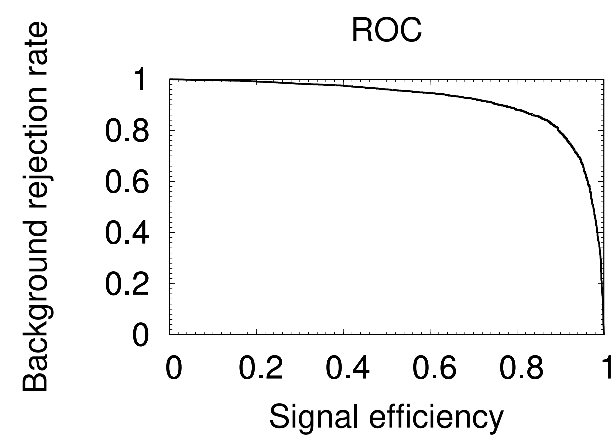
Ionization imaging for 0νββ

Simulated events in ^{136}Xe 0νββ energy region, ionization track in10bar Xe gas



Background discrimination using 3D track pattern information

Application of machine learning methods:



- High pressure gaseous TPC
- Pixelated direct ion (charge) readout, simultaneously achieving sufficient energy resolution and spatial resolution for tracking
- Ion drifting minimizes diffusion, but eliminates the possibility of charge amplification
- D. Nygren proposed SeF_6, low effective Z, positive and negative ions only as charge carrier
- Requires pixelated low noise (~10s e^-) charge readout → CMOS pixel direct charge sensor

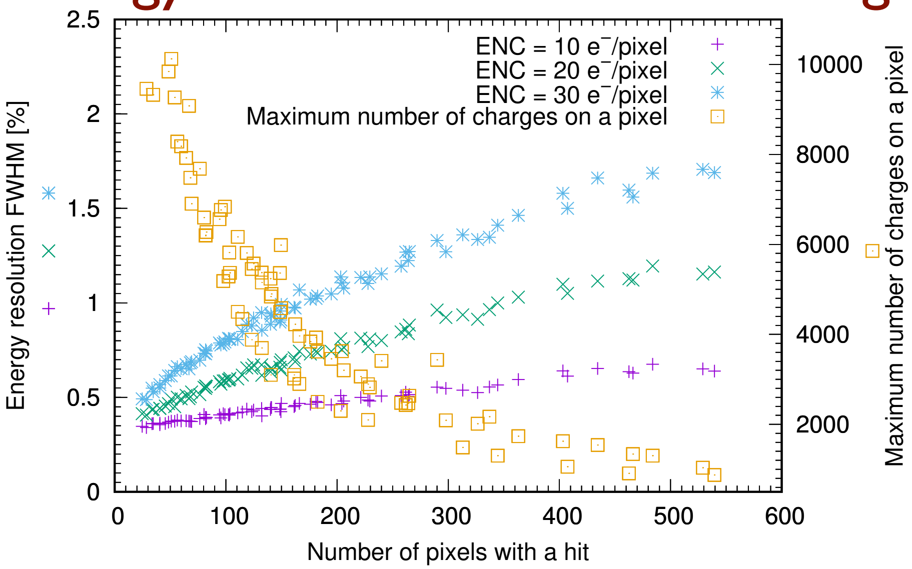
Numbers

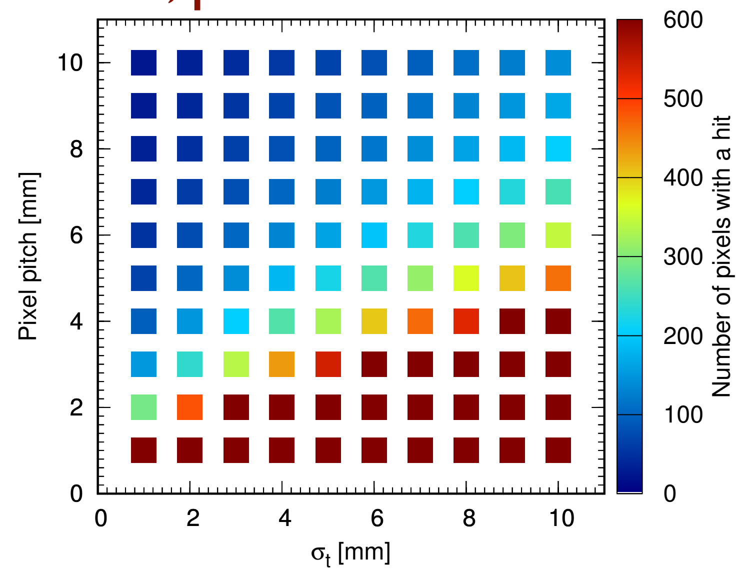
High pressure Xenon TPC as an example

- ~50 free ions/electrons per keV energy deposition
- ^{136}Xe $Q_{\beta\beta}$=2.458MeV → 100k charges
- 10bar Xe intrinsic energy resolution: 0.3% FWHM at $Q_{\beta\beta}$
  → 130 e^- total fluctuation (σ, detection medium contribution)
- 1% FWHM energy resolution at $Q_{\beta\beta}$ → 420 e^- fluctuation (σ)
  → 400 e^- electronic noise allowed (sum of all pixels)
- Track length 20~30cm → 300 pixels see charge if pitch 5~10mm
  → <30 e^- per pixel noise required
- 100% charge collection efficiency
  loss of efficiency is equivalent to increasing noise
- 10cm diameter array: ~100 chips
- 1m diameter array: ~10k chips
- Charge drifting speed (sets the sampling rate requirement)
  - Electron: mm/μs
  - Ion: mm/ms

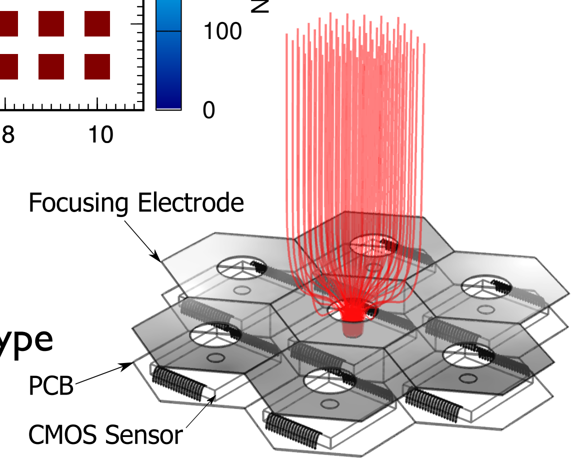
Design optimization

Energy resolution: tradeoff among diffusion, pixel size and noise

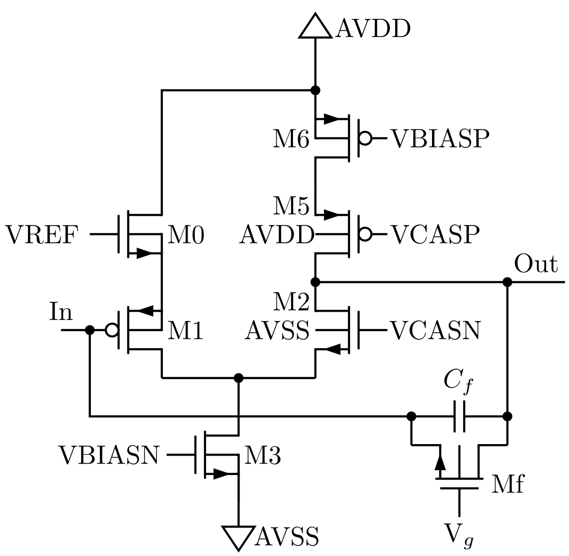


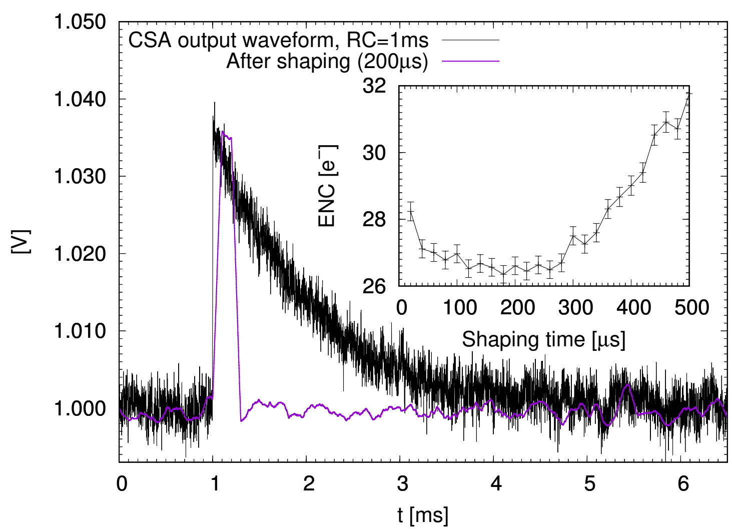


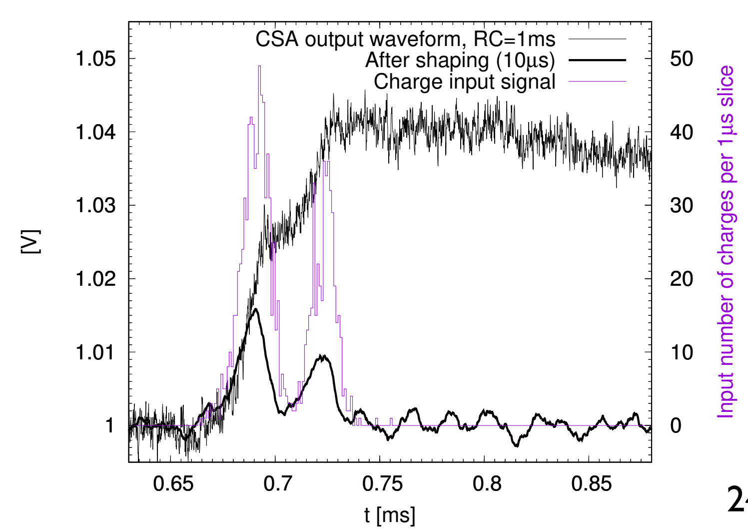
- 1mm dia. electrode
- 8mm pitch
- 127 chips on prototype



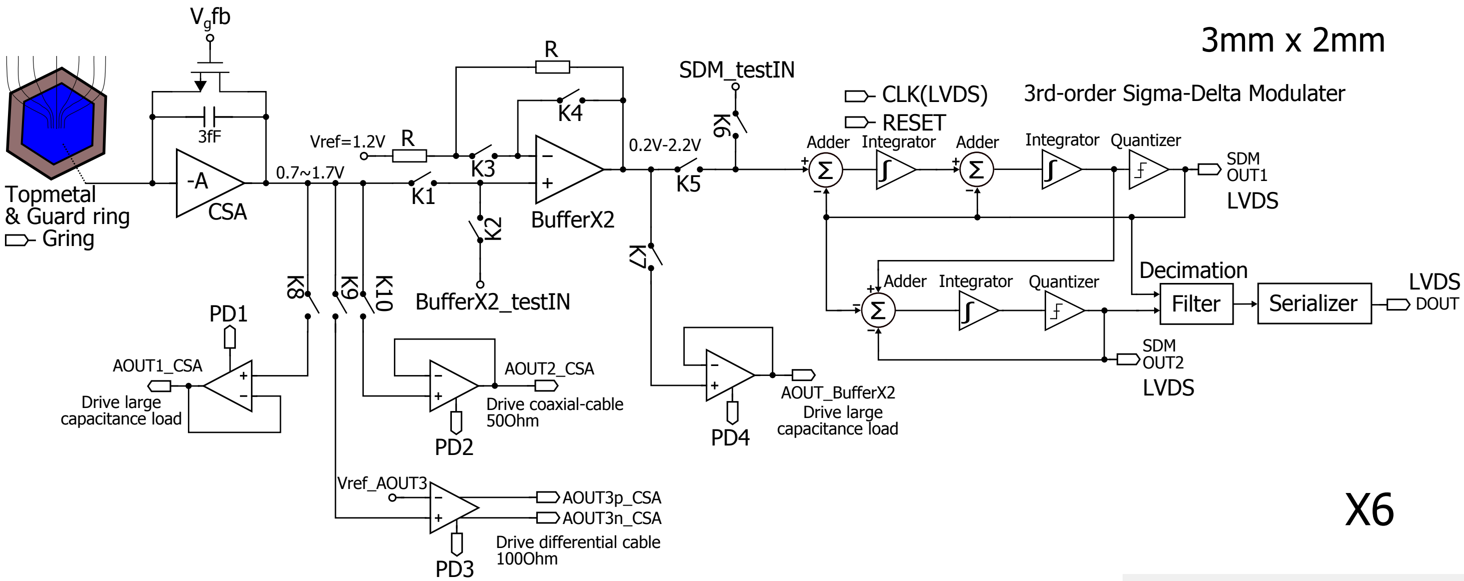
Charge measurement, noise, and signal recovery



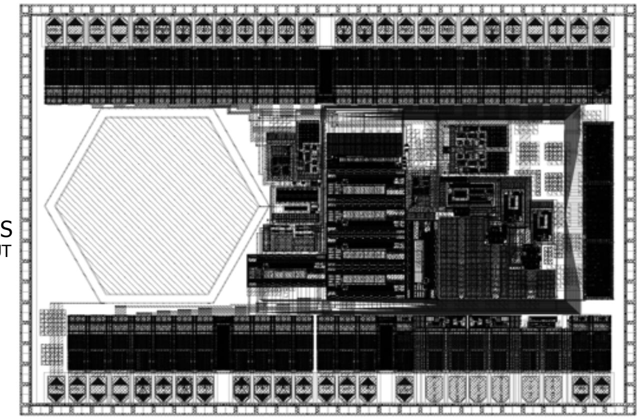




Topmetal-S (2016)

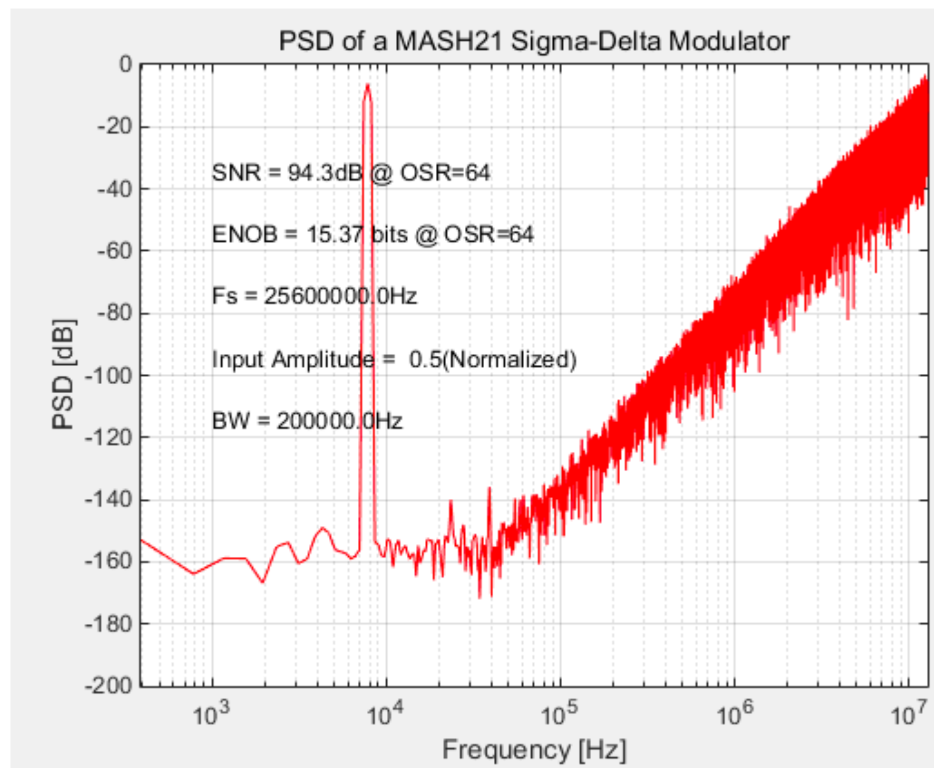


3mm x 2mm



X6

- •Single electrode: 1mm dia. *Topmetal* or smaller electrode with externally \`grown' structure
- •Distance between chips: 5~10mm
- •CSA: C_{in}~2pF, ENC<30e$^-$, tunable biases through DACs
- •Tunable feedback RC decay constant
- •Directly accessible analog output
- •Analog output (X2) feeds into a Sigma-Delta ADC



- •3rd-order Sigma-Delta Modulator
- •25.6MHz clock
- •X64 over sampling rate
- •SINC4 decimation filter
- •200kHz signal bandwidth
- •Equivalent of a 400ksps 16bit ADC
- •Raw modulator output
- •LVDS I/O

Summary

- Mature CMOS processes have become affordable and manageable
- Designing Integrated Circuit (IC) is becoming similar to designing Printed Circuit Board (PCB)
- Pack charge collection, processing and transmission functions right at the site of charge measurement, inside of the TPC
- High density system integration
- What's special about *Topmetal*
  - There are other CMOS sensors that can do similar things: Medipix, Timepix, FE-I3/4 etc.
  - We have a different aim: specifically optimize for low rate, low noise, and large scale charge readout, as well as other unexplored applications.
  - Create an entire package including both sensors and readout systems for physics applications.
- Since 2012
  - Two versions successfully produced and validated.
    - Explored beam measurement applications
  - Third version, *Topmetal-S*, produced. Being validated.
    - Develop integrated charge plane for $0\nu\beta\beta$ (current main effort)

End